université PARIS-SACLAY	School Ingénierie, sciences et technologies de l'information	Master Électronique, Énergie Électrique, Automatique

M2 ATSI — MASTER E3A

Control, Signal and Image Processing

Automatique, Traitement du Signal et des Images

Year 2023-2024

Chairs : Hugues Mounier & François Orieux

CURRICULUM DESCRIPTION

The **M2 ATSI (Control, Signal and Image Processing)** aims to train students to address academic and industrial research topics of a high scientific level in the domains of systems and control, signal and image processing. The courses focus on methodological foundations and recent developments in these fields, which intervene directly or indirectly in many disciplines such as optics, medicine, robotics, energy, automotive, … The curriculum also trains student to research work through dedicated teaching initiatives (seminars, bibliographic work, project, etc.) and a strong involvement of the associated research laboratories. Part of the training is given in English.

The M2 ATSI is part of the Master E3A of Université Paris-Saclay. This curriculum is also open to external recruitment, in particular in the context of double degrees with engineering schools (CentraleSupélec, IOGS), or for students from other national or international universities. As such, it is aimed at students with strong skills in the fields of engineering, in particular mastering and appreciating the theoretical aspects. It is also open to students with mathematics and possibly computer science degrees with a particular taste for application.

Students who follow this curriculum will have job opportunities in academic research as well as in industry. They will be able to pursue research training in the form of doctoral studies in academic or industrial environments (CIFRE thesis). They also will be able to work immediately as research engineer within industry R & D teams and specialized laboratories with needs in the areas of automation and control systems, signal and image processing or data science.

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PROGRAM

1st Semester

2 mandatory courses (block 1):

- Mathematical tools for control, signal and image processing
- Initiation to research

4 elective courses (block 2) among:

- Control of multivariable linear systems
- Estimation
- Optimization
- Signal representation and sparse coding
- Stability of nonlinear systems
- Signal processing and imaging systems

2nd Semester

4 elective courses (block 3) among:

- Machine learning
- Model predictive control
- Control and structural properties of nonlinear systems
- Control for robotics
- Robust statistics for signal processing
- Medical imaging
- Advanced methods in image processing
- Inverse problems
- Hybrid systems
- Multi-agent systems

1 internship (block 4) of 4 months duration minimum in academic or industrial environment.

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COURSES DESCRIPTION (1er Semestre)

Mathematical tools for control, signal and image processing

Head: Christophe Vignat
Teaching language: English/French
Teaching hours: 24h CM

The objective of this course is to allow students to master the mathematical foundation necessary to tackle academic or industrial research subjects, in the fields of control, signal and image processing.

Course summary:
Optimization and differential equations

- Optimization without and with constraints (gradient and Newton algorithms); Karush-Kuhn-Tucker conditions
- Non-linear ordinary differential equations (existence and uniqueness conditions)
- Stability; Lyapunov functions

Probability

- Probabilized space, events, independence; random variables; sequences of events, extreme events, Borel-Cantelli
- Mean values, moments, correlation, function of a random variable, conditional expectation; distribution function, probability density, characteristic function, generating function of moments and their inversions; continuous and discrete classical distributions
- Markov, Chebyshev inequalities; convergence types (weak, in probability, almost certain), weak and strong laws of large numbers, dominated convergence theorem, central limit theorem, law of the iterated logarithm

Algebra

- Types of matrices: rectangular, square, symmetric, Hermitian, orthogonal, unitary, positive definite, Hankel, Toeplitz, circulant, VanderMonde, diagonal, triangular, block-diagonal
- Matrix algebras: product, vectorization, invariants (determinant, trace, rank), block multiplication; matrix factorizations: Jordan, diagonalizability, triangularizability, Schur, QR, Cholesky, LU, spectral decomposition, singular value decomposition; least squares, pseudoinverse, normal equations
- Applications: matrix exponentials, systems of differential equations

Initiation to research

Heads: Hugues Mounier & François Orieux
Teaching language: English
Teaching hours: 24h CM

The purpose of this module is to introduce students to research work, in the fields of control, signal and image processing, through the following activities:

- 8 seminars on current research topics
- Bibliographic work related to one of the seminars
- A team mini-project

Control of multivariable linear systems

Head: Sihem Tebbani
Teaching language: French
Teaching hours: 20h CM + 6h TD

The aim of this course is to provide a solid foundation for the analysis and control of multivariable linear systems (MIMO systems: multi-input, multi-output), using both state space and transfer function representations. The main methods discussed are optimal control and estimation, robustness analysis and H-infinity control. The general idea is to provide all the means allowing an application on real systems (which can come from very different fields such as robotics, optics, automobiles, aeronautics ..., this list not being limiting), with an opening on research issues.

References:

[1] B.D.O. Anderson, J.B. Moore, Linear Optimal Control, Ed. Prentice-Hall, 1990.
[2] H. Kwakernaak, R. Sivan, Linear optimal control systems, Ed. Wiley, 1972.
[3] P. de Larminat, Commande des Systèmes Linéaires, Ed. Hermès, 1993.
[4] G. Duc, S. Font, Commande H-infini et mu-analyse, des outils pour la robustesse, Ed. Hermès, 1999.
[5] S. Skogestad and I. Postlethwaite. Multivariable Feedback Control: Analysis and Design. Ed. John Wiley and Sons, 1996, 2005.
[6] K. Zhou, J.C. Doyle, K. Glover, Robust and Optimal Control, Ed. Prentice-Hall, 1996.

Estimation

Head: Michel Kieffer
Teaching language: English
Teaching hours: 24h CM

The construction of parametric models and the determination of estimates of the vector of parameters from experimental data is at the core of the activity of engineers and researchers who wish to analyze physical phenomena, build software sensors, detect faults in a system, simulate a process, evaluate a command... The objective of this course is to make students aware of the difficulties associated with the parametric modeling and identification process, difficulties they are often not aware of. The course will provide elements of answers to the following questions: How to build a model of a system? For a given model structure, will it be possible to determine the value of its parameters in a unique way? When two model structures are competing, will it be possible to distinguish them? Once the structure of the model has been chosen, taking into account the knowledge available a priori, which criterion should be chosen to estimate the model parameters? How are the optimal value of these parameters obtained? A set of parameters has been obtained, but is it really the only one possible? How to quantify the parameter estimation uncertainty? How should the data collection be organized to obtain the best accuracy?

References:
[1] S. M. Kay, Fundamentals of Statistical Processing, Volume I: Estimation Theory, Prentice Hall, 1993.
[2] E. Walter and L. Pronzato, Identification of Parametric Models: From Experimental Data, Springer, 1997.
[3] E. Walter, Numerical methods and optimization: a consumer guide, Springer, 2014.
[4] L. Ljung and T. Glad, Modeling & Identification of Dynamic Systems, Prentice Hall, 2016.

Optimization

Heads: Laurent Le Brusquet & Jean-Christophe Pesquet
Teaching language: French
Teaching hours: 15h CM + 13,5h TD-TP

The main goal of this course is to provide basic concepts in optimization from theoretical and practical points of view. The focus is on continuous optimization methods that play a crucial role in signal and image processing and in automatic. These methods cover all areas of applications where one seeks to have a quantitative approach based on performance criteria. We will mention, in particular, resolution of inverse problems, machine learning, identification of complex systems, optimal control, ... In all these domains, it is not only necessary to know how to use efficient optimization algorithms, but also to think about the structure of the problem.

References:
[1] D. P. Bertsekas, Nonlinear Programming, 3rd Edition. Athena Scientific, 2016. ISBN:978-1-886529-05-2
[2] H.H. Bauschke and P. L. Combettes, Convex Analysis and Monotone Operator Theory in Hilbert Spaces, 2nd Edition. Springer, 2017. ISBN: 978-3-319-48311-5

Signal representation and sparse coding

Head: Matthieu Kowalski
Teaching language: English/French
Teaching hours: 18h CM + 9h TD-TP

The goal of this course is to present first different representations of the signals (Time, Frequency, time-frequency and time-scale), with their specificities. We will present the interest of orthonormal bases and frames for sparsity as well as the main algorithms allowing to obtain a sparse decomposition. The interest will be illustrated on a particular inverse problem, the compressed sensing. Finally, dictionary learning methods will be proposed for a class of signals and the utility in the inverse problems.

References:
[1] Mallat, S. (1999). A wavelet tour of signal processing. Elsevier.
[2] Foucart, S., & Rauhut, H. (2017). A mathematical introduction to compressive sensing. Bull. Am. Math, 54, 151-165.

Stability of nonlinear systems

Head: Giorgio Valmorbida
Teaching language: English
Teaching hours: 24h CM

The objective of this course is to provide tools for the analysis of nonlinear dynamical systems modelled by ordinary differential equations. These include engineering systems, such as robotic, automotive, and aerospace systems, but also biological and socio-economical systems. A key aspect of these equations is that their nonlinear nature usually prevents the calculation of an explicit solution. Furthermore, the frequency methods commonly used for linear systems do not apply in this context. We rely on stability theory to assess the qualitative behavior of dynamical systems. This course introduces specific stability notions and analysis tools tailored for nonlinear systems. Furthermore, beyond stability, these tools also enable to study the systems performance, robustness to disturbances, and interconnections.

References:
[1] Nonlinear Systems, Hassan Khalil, Pearson (3rd ed) 2001.
[2] Nonlinear Systems Analysis, M. Vidyasagar, SIAM Classics in Applied Mathematics (2nd edition), 2002.
[3] Ordinary Differential Equations, Part II, N. Rouche and J. Mawhin (Translation from : Équations Différentielles Ordinaires Tome II: Stabilité et Solutions Périodiques. Rouche, Nicolas, and Jean Mawhin. Paris: Masson, 1973).

Signal processing and imaging systems

Head: François Goudail
Teaching language: English
Teaching hours: 18h CM + 9h TD-TP

This course introduces the basic concepts of estimation and detection. For a better understanding, each of these concepts is illustrated on real problems related to optical imaging or image processing. This allows in particular to make more concrete the central notions of noise and optimality of treatments. The aim is that at the end of this course, a student will be able to formulate a problem of information extraction in a noisy signal or image in rigorous terms, to solve this problem in an optimal way, and to evaluate the performance of this solution.

References:
[1] Ph. Réfrégier, Noise Theory and Application to Physics: From Fluctuations to Information
(Springer, New-York, 2004).
[2] S. M. Kay, Fundamentals of statistical signal processing - Volume I : Estimation Theory
(Prentice-Hall, Englewood Cliffs, 1993).
[3] S. M. Kay, Fundamentals of statistical signal processing - Volume II : Detection Theory
(Prentice-Hall, Englewood Cliffs, 1993).
[4] F. Goudail, Ph. Réfrégier, Statistical image processing techniques for noisy images: an application oriented approach, (Kluwer Academic, New York, 2004).

Machine Learning

Head: Stéphane Herbin
Teaching language: French
Teaching hours: 12h CM + 18h TD-TP

Born in the 1950s with the advent of computers, machine learning has recently experienced a remarkable boom thanks to the availability of masses of data, great computing power (GPU) and specialized software environments (Deep Learning). Machine learning techniques have allowed a significant performance gain on classic problems of interpretation of complex data (image classification, face recognition, autonomous vehicle driving, speech recognition, translation, medical diagnosis, biometrics, etc.). This course consists in a general presentation of the main existing machine learning techniques, from the most classical to the most recent ones. It puts an emphasis on the practical implementation of these methods in various application domains through computer labworks and a project.

References:
[1] C. Bishop, Pattern Recognition and Machine Learning, (Springer-Verlag, 2006). (https://www.microsoft.com/en-us/research/uploads/prod/2006/01/Bishop-Pattern-Recognition-and-Machine-Learning-2006.pdf)
[2] Jerome H. Friedman, Robert Tibshirani et Trevor Hastie, The Elements of Statistical Learning: Data Mining, Inference, and Prediction (Springer-Verlag, 2009). (https://web.stanford.edu/~hastie/Papers/ESLII.pdf)
[3] Ian Goodfellow and Yoshua Bengio and Aaron Courville, Deep Learning, (An MIT Press book, 2016) (http://www.deeplearningbook.org).

Prerequisites:
In order to follow this course, it is necessary to have followed François Gouudail's first semester course "Signal processing and imaging systems" or to have assimilated the essential elements of estimation and detection, as set out in the following two books: S. M. Kay, Fundamentals of statistical signal processing - Volume I: Estimation Theory (Prentice-Hall, Englewood Cliffs, 1993) and S. M. Kay, Fundamentals of statistical signal processing - Volume II: Detection Theory (Prentice-Hall, Englewood Cliffs, 1993).

Model Predictive Control

Head: Sorin Olaru
Teaching language: English
Teaching hours: 18h CM + 9h TD-TP

Model predictive control is an advanced control method, based of models and optimization (optimal control). It has proven its performance on several industrial applications (more than 1000 applications identified in the early 2000s). At the same time, the theory has continued to evolve and many advances have been made, mainly on the improvement of robustness and real-time performance on the one hand, and on the extension to more complex structures / objectives on the other hand. The objective of this course is to present the classical or more recent results on model predictive control, which will allow the use of this technique as a methodological tool in automatic control. An important part of the course will be dedicated to the optimization and implementation aspect, where the taking into account of constraints leads to solve control problems by real time optimization techniques which are heavy in terms of computation even if the prediction models are linear. An alternative solution based on the search for explicit solutions for real-time implementation will be presented. In the second part, the course will deal with extensions to cover the notions of robustness of the prediction. Prediction in the presence of model uncertainties represents the key point of design but the mastery of computational complexity remains an unavoidable constraint. The course aims to raise awareness of the use of more complex models that take into account hybrid or non-linear dynamics in general.

References:
[1] Qin, S. Joe, and Thomas A. Badgwell. "A survey of industrial model predictive control technology." Control engineering practice 11.7 (2003): 733-764.
[2] Mayne, D. Q., Rawlings, J. B., Rao, C. V., & Scokaert, P. O. (2000). Constrained model predictive control: Stability and optimality. Automatica, 36(6), 789-814.
[3] Bemporad, A., Morari, M., Dua, V., & Pistikopoulos, E. N. (2002). The explicit linear quadratic regulator for constrained systems. Automatica, 38(1), 3-20.
[4] Mayne, D. Q., Seron, M. M., & Raković, S. V. (2005). Robust model predictive control of constrained linear systems with bounded disturbances. Automatica, 41(2), 219-224.
[5] Rawlings, J. B., & Mayne, D. Q. (2009). Model predictive control: Theory and design (pp. 3430-3433). Madison, Wisconsin: Nob Hill Pub.
[6] Fernandez-Camacho, E., & Bordons-Alba, C. (1995). Model predictive control in the process industry. Springer London.
[7] Boucher, P., & Dumur, D. (2006). La Commande Prédictive: Avancées et perspectives, Traité IC2.

Control and structural properties of nonlinear systems

Head: Paolo Mason
Teaching language: English
Teaching hours: 18h CM + 9h TD

The objective of this course is to present methodological and theoretical tools for control of nonlinear systems. The course is organized in two parts. In the first part, several classical nonlinear control design techniques are presented and illustrated with concrete examples. In the second part, an introduction to structural properties of nonlinear systems, such as controllability and observability, is given. Also, basic notions and tools of geometric control theory are introduced.

References:
[1] H. Khalil, Nonlinear systems, Prentice Hall, 2002
[2] A. Isidori, Nonlinear Control Systems, Springer, 1995
[3] M. Krstic , I. Kanellakopoulos , P. V. Kokotovic, Nonlinear and Adaptive Control Design, Wiley, 1995
[4] F. Bullo, A. D. Lewis, Geometric Control of Mechanical Systems, Springer, 2005 (chapter 3)
[5] E. D. Sontag, Mathematical Control Theory, Springer, New York, 1998

Control for robotics

Head: Hugues Mounier
Teaching language: English/French
Teaching hours: 24h CM/TP

This course aims to provide students with the basics of some trajectory tracking control methods with applications to robotics, but also to biological systems. The methodological techniques will be those of the differential flatness, particularly adapted to the synthesis of control ensuring the tracking of trajectories. The course is divided into two parts:

- In the first part, theoretical notions are developed and illustrated through examples and tutorials.
- In the second part, about twenty case studies, based on articles in the literature, are proposed to the students. For each system studied, one or more models are selected and for each, the differentially flat character is examined, a flat output is determined and a trajectory tracking is implemented in python language.

References:
[1] J. Levine, Analysis and Control of Nonlinear Systems: A Flatness based Approach, Springer, 2009
[2] H. Sira-Ramirez, S.K. Agrawal, Differentially Flat Systems, CRC Press, 2018

Robust statistics for signal processing

Head: Nabil El Korso
Teaching language: English
Teaching hours: 20h CM + 6h TD-TP

Nowadays, data are at the heart of many domains and their processing (e.g. for knowledge extraction, decision-making…) can be a very challenging problem, especially because data can be badly modeled, or at least, far from classical modeling. They can also contain outliers or part of the data can miss. To face such problems, the goals of this course is to provide to students advanced and recent techniques of robust statistics with several applications to classical problems in signal processing. More precisely, after a general introduction on monovariate robust estimation theory, we will move to the complex multivariate case adapted to signal processing applications. This course will mix the theoretical tools, such as robust estimation techniques, robust regressions and robust detection, as well as more signal processing focused applications: DOA estimation, signal filtering, signal detection, denoising…

References:
[1] Huber PJ (1981) Robust statistics. Wiley, New York

Medical imaging

Head: Nicolas Gac
Teaching language: English/French
Teaching hours: 18h CM + 9h TD-TP

The aim of this course is to develop practical and theoretical skills of estimation and resolution of inverse problems for medical imaging. The courses will focus on the main medical imaging modalities, which are MRI, and nuclear medicine as SPECT and PET imaging. This course will be divided into two parts, the first on imaging from MRI devices and the second on nuclear imaging. Moreover, as the reconstructions in this area require very important computing resources, a practical work session will be dedicated to the parallelization of algorithms on a massively parallel machine (GPU).

Advanced methods in image processing

Head: Florence Tupin
Teaching language: English/French
Teaching hours: 18h CM + 9h TD-TP

The objective of this course is to present basic models of image processing (sampling, contour detection) and to give an overview of the major problems of the field (restoration, denoising, segmentation) and usual methods (mathematical morphology, filtering, Markov fields).

References:

[1] H. Maître, Le traitement des images (Hermès,2002).
[2] C. Aguerrebere et al., Simultaneous HDR reconstruction and denoising of dynamic scenes, ICCP 2013.

Inverse problems

Head: Thomas Rodet
Teaching language: English/French
Teaching hours: 18h CM + 9h TD-TP

A large part of signal processing can be seen from the point of view of inversion, in the sense that the observations are partly informative on the quantity to be estimated and the estimation is also based on physical models. In various applications such as astrophysics, biomedical engineering, industrial monitoring or remote sensing, the direct use of measurements is not always satisfactory. Inversion methods make possible to take into account distortions introduced by the measuring devices in order to reconstruct the quantity of interest. This course addresses ill posed inverse problems, for which the observed data are insufficient to reliably reconstruct the object of interest. Regularization techniques are then necessary to solve these difficult problems. We introduce two major families of methods. On the one hand variational approach, based on the construction and optimization of a regularized cost function and on the other Bayesian approach, based on the probabilistic modeling of the object to be reconstructed and the errors of model. This latter approach leads to unsupervised methods for quantifying uncertainties. The different underlying approaches and algorithms will be illustrated on different case studies (TP) such as the restoration or reconstruction of signals and images with linear direct models or not. Application areas related to these case studies will be biomedical engineering, nondestructive testing or image processing in astrophysics.

References:
[1] J. Idier. « Approche bayésienne pour les problèmes inverses , Traité IC2, Série traitement du signal et de l'image, Hermès, Paris, nov. 2001.
[2] J. F. Giovannelli et J. Idier, « Méthodes d'inversion appliquées au traitement du signal et de l'image », Hermès, Paris, nov. 2013.
[3] J. Nocedal et S. J. Wright, « Numerical optimization », Springer texts in Operations Research and Financial Engineering, 2ème édition, Springer Verlag, New York, juil. 2006.
[4] C. P. Robert, « Le choix bayésien », Coll. Statistique et probabilités appliquées, Springer,
Paris, 2006.
[5] V. Smidl et A. Quinn, « The variational Bayes method in signal processing », Springer, Berlin, 2006.

Hybrid systems

Head: Luca Greco
Teaching language: English
Teaching hours: 18h CM + 9h TD-TP

Hybrid dynamics, combining event-based and classical dynamics (in continuous or discrete time), are common to many physical systems such as transport systems, production lines, biochemical reactors, neurons, etc. They also give rise to many control applications: supervised control, gain scheduling, quantization or sampling effects, network-controlled systems, degraded modes, and so on. The purpose of this course is to present the basic concepts necessary for the analysis and control of hybrid systems. It focuses on three formalisms: switching systems, piecewise affine systems and hybrid automata. Each concept will be illustrated by an application example from the automotive industry.

References:
[1] Liberzon, D., (2003). Switching in systems and control. Springer Science & Business Media.
[2] Lygeros, J., Johansson, K. H., Simic, S. N., Zhang, J., & Sastry, S. S. (2003). Dynamical properties of hybrid automata. IEEE Transactions on automatic control, 48(1), 2-17.
[3] Tomlin, C. J., Lygeros, J., & Sastry, S. S. (2000). A game theoretic approach to controller design for hybrid systems. Proceedings of the IEEE, 88(7), 949-970.

Multi-agent systems

Head: Ioannis Sarras
Teaching language: English/French
Teaching hours: 18h CM + 9h TD-TP

Animal swarms, electric grids, autonomous vehicle formations, interconnected neurons, sensor networks… all these systems share a crucial feature: their overall behavior results from a local interaction among many agents. Here, "local" means that each agent typically interacts with its neighbors only. This course aims at providing the basics to both analyze and control of such large-scale networks. In particular, it provides methodological tools to study interconnection between multiple dynamical agents. It addresses two fundamental features of such networks: consensus, in which the states of all agents converge to a common value, and synchronization, in which agents share a coherent behavior (possibly non-static). These notions will be illustrated via a selection of case studies.

References:

[1] W. Ren, Y. Cao. Distributed Coordination of Multi-agent Networks: Emergent Problems, Models, and Issues. Communications and Control Engineering, Springer-Verlag, London, 2011
[2] W. Ren, R.W. Beard, and E. M. Atkins. Information Consensus in Multivehicle Cooperative Control, IEEE Control Systems Magazine, Vol. 27, No. 2, April, 2007, pp. 71-82
[3] Henk, N. and Alejandro, R. A.. Synchronization of mechanical systems (Vol. 46), World Scientific, 2003
[4] S.S Kia, B.VanScoy, J.Cortes, R.A. Freeman, K.M. Lynch, and S.Martinez. Tutorial on Dynamic Average Consensus The problem, its applications, and the algorithms, arXiv 2018