RESEARCH CENTRE

Inria Saclay Center at Université Paris-Saclay

IN PARTNERSHIP WITH:

CNRS, Université Paris-Saclay

2022 ACTIVITY REPORT

Project-Team DISCO

Dynamical Interconnected Systems in COmplex Environments

IN COLLABORATION WITH: Laboratoire des signaux et systèmes (L2S)

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Optimization and control of dynamic systems

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Project-Team DISCO

Creation of the Project-Team: 2012 January 01

Keywords

Computer sciences and digital sciences

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1 Team members, visitors, external collaborators

Research Scientists

- Catherine Bonnet [Team leader, INRIA, Senior Researcher, HDR]
- Joseph Frederic Bonnans [INRIA, Senior Researcher, HDR]
- Guilherme Mazanti [INRIA, Researcher]
- Frederic Mazenc [INRIA, Senior Researcher, HDR]
- Laurent Pfeiffer [INRIA, Researcher]

Faculty Members

- Islam Boussaada [IPSA, Professor, HDR]
- Silviu-Iulian Niculescu [CNRS, Professor, HDR]
- Giorgio Valmorbida [CENTRALESUPELEC, Associate Professor]

PhD Students

- Amina Benarab [UNIV PARIS SACLAY]
- Kang Liu [Ecole Polytechnique]
- Thibault Moquet [CENTRALESUPELEC, from Oct 2022]
- Jeanne Redaud [CENTRALESUPELEC]
- Saeed Sadeghi Arjmand [ECOLE POLY PALAISEAU]

Interns and Apprentices

- Thibault Moquet [CENTRALESUPELEC, from Apr 2022 until Sep 2022]

External Collaborator

- Ali Zemouche [UL, HDR]

2 Overall objectives

2.1 Objectives

The goal of the project is to better understand and well formalize the effects of complex environments on the dynamics of the interconnections, as well as to develop new methods and techniques for the analysis and control of such systems.

It is well-known that the interconnection of dynamic systems has as consequence an increased complexity of the behavior of the total system.

In a simplified way, as the concept of dynamics is well-understood, the interconnections can be seen as associations (by connections of materials or information flows) of distinct systems to ensure a pooling of the resources with the aim of obtaining a better operation with the constraint of continuity of the service in the event of a fault. In this context, the environment can be seen as a collection of elements, structures or systems, natural or artificial constituting the neighborhood of a given system. The development of interactive games through communication networks, control from distance (e.g. remote surgical operations) or in hostile environment (e.g. robots, drones), as well as the current trend of large scale integration of distribution (and/or transport and/or decision) and open information systems with systems of production, lead to new modeling schemes in problems where the dynamics of the environment have to be taken into account.

In order to tackle the control problems arising in the above examples, the team investigates new theoretical methods, develops new algorithms and implementations dedicated to these techniques.

3 Research program

3.1 Analysis of interconnected systems

The major questions considered are those of the characterization of the stability (also including the problems of sensitivity compared to the variations of the parameters) and the determination of stabilizing controllers of interconnected dynamic systems. In many situations, the dynamics of the interconnections can be naturally modelled by systems with delays (constant, distributed or time-varying delays) possibly of fractional order. In other cases, partial differential equations (PDE) models can be better represented or approximated by using systems with delays. Our expertise on this subject, on both time and frequency domain methods, allows us to challenge difficult problems (e.g. systems with an infinite number of unstable poles).

- Robust stability of linear systems

  Within an interconnection context, lots of phenomena are modelled directly or after an approximation by delay systems. These systems may have constant delays, time-varying delays, distributed delays.

  For various infinite-dimensional systems, particularly delay and fractional systems, input-output and time-domain methods are jointly developed in the team to characterize stability. This research is developed at four levels: analytic approaches (H_∞-stability, BIBO-stablity, robust stability, robustness metrics) [2, 1, 6, 7], symbolic computation approaches (SOS methods are used for determining easy-to-check conditions which guarantee that the poles of a given linear system are not in the closed right half-plane, certified CAD techniques), numerical approaches (root-loci, continuation methods) and by means of softwares developed in the team [6, 7].

- Robustness/fragility of biological systems

  Deterministic biological models describing, for instance, species interactions, are frequently composed of equations with important disturbances and poorly known parameters. To evaluate the impact of the uncertainties, we use the techniques of designing of global strict Lyapunov functions or functional developed in the team.

  However, for other biological systems, the notion of robustness may be different and this question is still in its infancy (see, e.g. [85]). Unlike engineering problems where a major issue is to maintain stability in the presence of disturbances, a main issue here is to maintain the system response in the presence of disturbances. For instance, a biological network is required to keep its functioning in case of a failure of one of the nodes in the network. The team, which has a strong expertise in robustness for engineering problems, aims at contributing at the develpment of new robustness metrics in this biological context.

3.2 Stabilization of interconnected systems

- Linear systems: Analytic and algebraic approaches are considered for infinite-dimensional linear systems studied within the input-output framework.

  In the recent years, the Youla-Kučera parametrization (which gives the set of all stabilizing controllers of a system in terms of its coprime factorizations) has been the cornerstone of the success of the H_∞-control since this parametrization allows one to rewrite the problem of finding the optimal stabilizing controllers for a certain norm such as H_∞ or H_2 as affine, and thus, convex problem.

A central issue studied in the team is the computation of such factorizations for a given infinite-dimensional linear system as well as establishing the links between stabilizability of a system for a certain norm and the existence of coprime factorizations for this system. These questions are fundamental for robust stabilization problems [2, 1].

We also consider simultaneous stabilization since it plays an important role in the study of reliable stabilization, i.e. in the design of controllers which stabilize a finite family of plants describing a system during normal operating conditions and various failed modes (e.g. loss of sensors or actuators, changes in operating points). Moreover, we investigate strongly stabilizable systems, namely systems which can be stabilized by stable controllers, since they have a good ability to track reference inputs and, in practice, engineers are reluctant to use unstable controllers especially when the system is stable.

- Nonlinear systems

  In any physical systems a feedback control law has to account for limitation stemming from safety, physical or technological constraints. Therefore, any realistic control system analysis and design has to account for constraints appearing mainly from sensors and actuators nonlinearities and from the regions of safe operation in the state space. This motivates the study of linear systems with more realistic, thus complex, models of actuators accounting for saturation and quantization at the inputs of the system [11], [8], [12].

  The project aims at developing robust stabilization theory and methods for important classes of nonlinear systems that ensure good controller performance under uncertainty and time delays. The main techniques include techniques called backstepping and forwarding, contructions of strict Lyapunov functions through so-called "strictification" approaches [4] and construction of Lyapunov-Krasovskii functionals [5, 6, 7] or or Lyapunov functionals for PDE systems [10].

3.3 Synthesis of reduced complexity controllers

- PID controllers

  Even though the synthesis of control laws of a given complexity is not a new problem, it is still open, even for finite-dimensional linear systems. Our purpose is to search for good families of "simple" (e.g. low order) controllers for infinite-dimensional dynamical systems. Within our approach, PID candidates are first considered in the team [1], [90].

  For interconnected systems appearing in teleoperation applications, such as the steer-by-wire, Proportional-Derivative laws are simple control strategies allowing to reproduce the efforts in both ends of the teleoperation system. However, due to delays introduced in the communication channels these strategies may result in loss of closed loop stability or in performance degradation when compared to the system with a mechanical link (no communication channel). In this context we search for non-linear proportional and derivative gains to improve performance. This is assessed in terms of reduction of overshoot and guaranteed convergence rates.

- Delayed feedback

  Control systems often operate in the presence of delays, primarily due to the time it takes to acquire the information needed for decision-making, to create control decisions and to execute these decisions. Commonly, such a time delay induces desynchronizing and/or destabilizing effects on the dynamics. However, some recent studies have emphasized that the delay may have a stabilizing effect in the control design. In particular, the closed-loop stability may be guaranteed precisely by the existence of the delay. The interest of considering such control laws lies in the simplicity of the controller as well as in its easy practical implementation. It is intended by the team members to provide a unified approach for the design of such stabilizing control laws for finite and infinite dimensional plants [3, 9].

- Finite Time and Interval Observers for nonlinear systems

  We aim to develop techniques of construction of output feedbacks relying on the design of observers. The objectives pertain to the design of robust control laws which converge in finite time, the construction of intervals observers which ensure that the solutions belong to guaranteed intervals, continuous/discrete observers for systems with discrete measurements and observers for systems with switches.

Finally, the development of algorithms based on both symbolic computation and numerical methods, and their implementations in dedicated Scilab/Matlab/Maple toolboxes are important issues in the project.

4 Application domains

4.1 Analysis and Control of life sciences systems

The team is involved in life sciences applications. The two main lines are the analysis of bioreactors models (microorganisms; bacteria, microalgae, yeast, etc..) and the modeling of cell dynamics in Acute Myeloblastic Leukemias (AML) in collaboration with St Antoine Hospital in Paris.

4.2 Energy Management

The team is interested in Energy management and considers control problems in energy networks.

4.3 Transportation Systems

The team is interested in control applications in transportation systems. In particular, the problem of collision avoidance of autonomous vehicels has been investigated under the framework of Time Varying systems. The goal is to obtain closed-loop control laws that guarantee the execution of a trajectory under uncertainties such as road and vehicle conditions.

5 New software and platforms

5.1 New software

5.1.1 P3δ

Name: Partial pole placement via delay action

Keywords: Delay systems, Control design, Automatic control

Functional Description: A Python implementation of recent methods for the stability analysis and stabilization of linear time-delay systems exploiting the delay action. Its control design strategy is based on properties of the spectral distribution of the time-delay system.

Release Contributions: Generic and control-oriented MID

URL: https://iboussaa.gitlabpages.inria.fr/partial-pole-placement-via-delay-action/P3d-Home.html

Authors: Guilherme Mazanti, Islam Boussaada, Silviu-Iulian Niculescu

Contact: Islam Boussaada

Partners: Cyb'Air-IPSA, ICODE, CentraleSupélec

5.1.2 YALTAPy

Keywords: Linear system, Delay systems, Stability, Fractional system

Scientific Description: YALTAPy is a Python Toolbox dedicated to the stability analysis of (fractional) delay systems given by their transfer function.

The delays are supposed to be commensurate.

In the case of retarded systems or of neutral systems with asymptotic axes in the left half-plane, YALTAPy gives: – For a given delay , the number and the position of unstable poles. – For which values of the delay the system is stable, – For a set of values of the delay, the position of unstable poles (root locus).

Functional Description: The YALTAPy toolbox is a Python toolbox dedicated to the study of classical and fractional systems with delay in the frequency-domain. Its objective is to provide basic but important information such as, for instance, the position of the neutral chains of poles and unstable poles, as well as the root locus with respect to the delay of the system.

YALTAPy_Online is an online version of YALTAPy

Publication: hal-00766550

Authors: Catherine Bonnet, Guilherme Mazanti, Hugo Cavalera

Contact: Catherine Bonnet

5.1.3 YaltaPy Online

Keywords: Linear system, Delay systems, Stability, Fractional system

Scientific Description: YALTAPy_Online is an online version of YALTAPy

Functional Description: YALTAPy_Online is an online version of YALTAPy

Authors: Catherine Bonnet, Guilherme Mazanti, Jayvir Raj

Contact: Catherine Bonnet

6 New results

6.1 Spectral properties and partial pole placement for time-delay systems

Participants: Amina Benarab *(DISCO)*, Catherine Bonnet *(DISCO)*, Islam Boussaada *(DISCO)*, Hugo Cavalera *(DISCO)*, Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Sébastien Fueyo *(DISCO)*, Ayrton Hammoumou *(IPSA, France)*, Julien Huynh *(IPSA, France)*, Guilherme Mazanti *(DISCO)*, Titouan Millet *(IPSA, France)*, Silviu-Iulian Niculescu *(DISCO)*, Jayvir Raj *(IPSA, France)*.

Linear time-invariant time-delay systems are infinite-dimensional and, as such, their spectra contains infinitely many values, which can be characterized as sets of roots of quasipolynomials. Understanding the location of such roots provides valuable information on the stability of the underlying time-delay system and is a fundamental step for the design of stabilizing feedback control laws [84, 89].

Several techniques for the stability analysis of time-delay systems through spectral methods developed on the DISCO team along the years were implemented in the Matlab toolbox YALTA [77]. This toolbox was converted along the previous years into a Python toolbox, called YALTAPy, for which a friendly online graphical user interface, YALTAPy_Online was developed during the last year. The publication [45] provides a description of YALTAPy and YALTAPy_Online, presenting their main features and instructions of use.

Pole placement represents a classical method for controlling finite-dimensional linear time invariant systems. Basically, it consists of placing the poles of the closed-loop system in some predetermined loci in the complex plane. An overview of the extensions of this method to linear systems described by delay-differential equations is provided in [41]. Among others, the finite spectrum assignment, the continuous pole placement and the partial pole placement approaches are presented and their limitations discussed. s

Since the seminal works [78, 79], it has been known that roots of quasipolynomials of large multiplicity are often dominant, a property which came to be known as the *multiplicity-induced-dominancy* (MID) property. The most general result concerning the MID property for roots with the maximal possible multiplicity of systems with a single delay was established in [17], showing that, in such a situation of maximal multiplicity, the MID property always holds true. The proof of such a result relies on the links between the spectrum of a time-delay system with a root of maximal multiplicity and Kummer confluent hypergeometric funcions. By exploiting in addition properties of Padé approximations of the exponential function, the recent work [58] has presented a simplified proof of that result.

Another challenging problem is the study of the MID property for roots with multiplicity smaller than the maximal one (IMID for Intermediate Multiplicity Induced Dominancy). By exploring in more details the ideas from [17], the work [43] provides new insights for the dominance of roots with multiplicity smaller than the maximal one, using the Green–Hille transformation to provide interesting results on the distribution of nonasymptotic zeros of linear combinations of Kummer functions. Also, the MID and IMID properties for second-order neutral time-delay differential equations with a single delay have been fully characterized in [14]. The control methodology is summarized in a five-steps algorithm that can be exploited in the design of higher-order systems. It has been shown how the stabilization of the classical oscillator benefits from the obtained results.

Studying the MID property for systems with more than one delay is a challenging question, which is addressed in [71] for first-order systems with two delays. By considering the ratio between the smallest and the largest delay as a parameter, [71] provides a careful analysis of the behavior of the spectrum of the system with respect to this parameter, which is used to establish the MID property for roots of maximal multiplicity of such a class of systems. As a consequence, [71] also establishes that the inclusion of a second delay may help in stabilizing time-delay systems with constraints on their coefficients, with respect to a classical proportional-delayed controller.

Stabilization methods for time-delay systems based on the MID property, as well as on the related coexisting-real-roots-induced-dominancy (CRRID) property, are implemented in the DISCO Team software P3δ, which is constantly updated with new features both to include new results available in the litterature and to improve user experience with the software. The paper [44] provides a description of the features recently implemented in the software, including in particular delaied studies of some examples of application of P3δ in the stabilization of systems stemming from applications.

6.2 PID tuning for controlling delayed dynamics

Participants: Catherine Bonnet, Islam Boussaada, Jianqui Chen *(L2S, City University of Hong Kong, China)*, Jie Chen *(L2S, City University of Hong Kong, China)*, Dan Ma *(Northeastern University, China)*, Silviu-Iulian Niculescu.

Nowadays, the PID controller is the most used in controlling industrial processes. In [ma:hal-02479679], the MID property which is merely a delayed-output-feedback where the candidates delays and gains result from the manifold defining the maximal multiplicity of a real spectral value, is employed in the PID tuning for delayed plants. More precisely, the controller gains (k_p, k_i, k_d) are tuned using the intentional multiplicity algebraic constraints allowing the stabilization of unstable delayed plants. The specificity of such a design is related to the analytical assignment of the closed-loop solution decay rate additionally to its robustness with respect to uncertain parameters.

6.3 Linear switched systems with deterministic or probabilistic switching

Participants: Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Guilherme Mazanti *(DISCO)*, Pierre Monmarché *(LJLL & LCT, Sorbonne Université, France)*, Mario Sigalotti *(Inria & LJLL, Sorbonne Université, France)*.

Due to interaction with discrete phenomena, several control systems may operate under the presence of switching signals, which typically have an important impact on stability (see, e.g., [87]). Among the strategies used in the literature to address the effects on stability of unknown switching signals, one can find probabilistic models, such as Markov switching, as well as robust notions of stability, such as stability under arbitrary switching. While it is clear that the latter is in general a more conservative measure of stability than the former, understanding in which situation there is a real advantage in considering the probabilistic framework is a nontrivial question.

This questions was addressed for continuous-time switched systems in [70]. More precisely, that work compares deterministic and probabilistic Lyapunov exponents for linear switched systems in finite dimensions. The major difficulty in this analysis comes from understanding the limiting behavior of arbitrarily fast switching. From the probabilistic point of view, this amounts to analyzing the behavior of Markov processes with fast switching, which is done in that work by nontrivial adaptations of results from various works by C. Landim and collaborators, in particular [86], which consider instead Markov processes under slow switching. Thanks to this analysis, [70] shows that the Markovian switching framework tends to be "more stable" than the robust deterministic point of view, except in some very particular situations, which are completely characterized in dimensions 2 and 3. Partial results are also provided in higher dimensions.

6.4 Controllability of difference equations

Participants: Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Sébastien Fueyo *(Inria & LJLL, Sorbonne Université, France)*, Guilherme Mazanti *(DISCO)*, Mario Sigalotti *(Inria & LJLL, Sorbonne Université, France)*.

Difference equations are mathematical models for systems in which the state at a given time is a function of the same state at previous times and of control inputs. They can be seen as the simplest form of neutral time-delay systems, in which no derivatives are present in the model, and they also appear naturally when studying some hyperbolic partial differential equations in one space dimension. When its delays are commensurable, the controllability of a difference equation is easy to study, and can be characterized by a Kalman-like criterion [82]. However, the problem is more delicate for difference equations with uncommensurable delays. The work [69] makes use of the realization theory, and in particular a series of works by Y. Yamamoto, to provide characterizations of exact and approximate controllability in L^p spaces. Approximate controllability in L^p is completely characterized by a Hautus-type criterion, and the "closure" of such a criterion is shown to be a sufficient condition for exact controllability in L^1. A key step to establish these results is to study the range of the endpoint map, which is done thanks to the representation formula for solutions of difference equations provided in [82] and a generalization of the Cayley–Hamilton theorem to multivariate polynomials, and also yields upper bounds on the controllability time.

6.5 State transition matrix

Participants: Michael Malisoff *(LSU)*, Frédéric Mazenc.

Determining fundamental matrices of time-varying linear systems is in general a difficult task, notably when disturbances are present. This prompted us to construct upper and lower bounds for the fundamental matrices. This problem is studied in [23], [25] and [47]. In [23], for both continuous-time and discrete-time systems, bounds are provided and used to solve stabilization and observer design problems. In [25] and [47], we obtained less conservative bounds than those of [23] and we introduced the notion of "full Metzler matrix" and used it to produce bounds given by simple expressions. The results have been applied to a control problem for a model arising from a marine robotic application.

6.6 Event-triggered control

Participants: Frédéric Mazenc, Michael Malisoff *(LSU)*, Corina Barbalata *(LSU)*, Zhong Ping Jiang *(Tandon School)*.

Event-triggered control has the advantage that it can reduce computational burdens of implementing feedback controls, by only changing control values when a significant enough event occurs. In order to decrease the number of needed switches of the control laws, we developed several results relying on the theory of the positive systems and comparison systems called interval observers. In several papers, [27], [28], [29], [30], [34], we addressed the case of continuous-time linear systems with delay, discrete-time systems, time-varying systems.

6.7 Halanay's inequality

Participants: Frédéric Mazenc, Michael Malisoff *(LSU)*, Miroslav Krstic *(Univ. California)*.

We developed in the contributions [31], [26] and [24] a stability analysis techniques to enable to prove stability in cases where traditional techniques, such as Lyapunov techniques, do not apply. It is based on variant of the celebrate Halanay's inequality, which is especially useful for ordinary differention equations in which a time-varying delay is inserted. In particular, we obtained vector versions of Halanay's inequality result.

6.8 Stability Analysis of Delay Systems with Lyapunov-Krasovskii methods

Participants: Giorgio Valmorbida, Ali Diab *(Ampère - Lyon)*, William Pasillas-Lepine *(Laboratoire des Signaux et Systèmes)*.

In the context of tele-operated systems, in particular for steer-by-wire systems, delays are critical for the stability of the closed loop. To design non-linear control strategies that allow to satisfy the requirements related to driving comfort, we need design methods based on a time-domain approach, in particular approaches based on Lyapunov-Krasovskii function computation. However, the existing numerical methods to compute Lyapunov-Krasovskii functions to certify stability of a delay system are limited since they do not correspond to the necessary and sufficient conditions of the analytical conditions.

We formulated a numerical test based on projections on generic function basis to compute the parameters of the Lyapunov Delay function. Our tests encompass existing approaches and provide superior results for examples in the literature in terms of delay margin enlargement. We are currently working towards the extension of these analysis results to the control design problems and to the analysis of discrete-time system.

6.9 Stability analysis of Piece-Wise Affine Systems

Participants: Giorgio Valmorbida, Joao Manoel Gomes da Silva Jr *(Universidade Federal do Rio Grande do Sul)*, Francesco Ferrante *(Università di Perugia)*.

Piece-wise affine systems appear when linear dynamics are defined in different partitions of the state space. This type of system naturally appears whenever actuators have different stages or saturate or whenever non-linear control laws are obtained as the solution to a parameterised optimization problem as, for instance for systems with feedback laws based on the so-called explicit Model Predictive Control. Even though the dynamics is simple to describe, the stability analysis, performance assessment and robustness analysis are difficult to perform since, due to the often used explicit representation, the Lyapunov stability and dissipation tests are often described in terms of a number of inequalities that increase exponentially on the number of sets in the partition since they are based on the enumeration of the partition transitions. Moreover regional stability and uncertainties corresponding to modification on the partition are difficult to study in this scenario.

To overcome these difficulties we have proposed an implicit representation for this class of systems in terms of ramp functions. The main advantage of such a representation lies on the fact that the ramp function can be exactly characterized in terms of linear inequalities and a quadratic equation, namely a linear complementarity condition. Thanks to the characterization of the ramp function and the implicit description of the PWA system the verification of Lyapunov inequalities related to piecewise quadratic functions can be cast as a pair of linear matrix inequalities. We are now applying the results to the local analysis and synthesis of PWA control laws. These results generalise the local analysis of saturating systems and avoid the complexity of PWA system analysis which is currently based on enumeration of the transition in a PWA partition.

We have also shown that the step function can be written as an ill-posed algebraic loop with two ramp functions. We were thus able to unify the analysis of continuous and discontinuous PWA functions and thus to perform the analysis with partition-based Lyapunov functions. As a first case to apply the developed methodology, we have studied the class of systems with ternary inputs. Thanks to the representation in terms of ramp functions, we are working towards an unified representation for the evaluation, analysis and design of discontinuous PWA dynamics, including switched systems.

More recently, we have shown that Convex Quadratic Programs can be written as an implicit equation involving ramp functions. For specific examples of QP-Model Predictive Control, we obtained solutions to the implicit equation with a speed up factor of 20-100 with respect to a standard QP interior-point solver or over active set methods using compiled code. We are now investigating the relations of other finite-step convergence algorithms for PWA equations and the method we proposed. Moreover, we aim to formalize the approximation schemes obtained with simple iterative methods to obtain rigorous bounds to approximate MPC strategies and assess its effect when these approximations are used in closed loop.

6.10 Advanced observers design: Certified decay and finite-time convergence

Participants: Frédéric Mazenc, Silviu Niculescu, Michael Malisoff *(LSU)*.

In order to estimate the state of a dynamical system, we address in [60] the problem of designing an observer for linear time-invariant (LTI) dynamical systems including a time-delay. Sufficient conditions for the existence of the proposed observer are given using partial placement of the poles for the error. Namely, we exploit the multiplicity-induced-dominance property of the characteristic function corresponding to the system's error. The effectiveness of the proposed observer design is shown in both state lag and input lag respectively through the problems of Mach number control in a wind tunnel and stabilization of the inverted pendulum on a cart by using the delay

To improve asymptotic observers which give a valuable information only after a transient period which can be long, we designed observers that converge in a fixed finite time or almost in fixed finite time.

In [35], we studied continuous-time nonlinear systems with discrete measurements, model uncertainty, and sensor noise and provided an estimator of the state for which the observation error enjoys a variant of the exponential input-to-state stability property with respect to the model uncertainty and sensor noise. The main result is illustrated via a model for a pendulum whose suspension point is subjected to an unknown time-varying bounded horizontal oscillation.

In [32], we provided observers for a class of nonlinear systems which are not required to be affine in the unmeasured states. The observers ensure exponential convergence of the observation errors to zero. The rate of exponential convergence converges to infinity, as the growth rate of the nonlinear state-dependent part of the dynamics converges to zero, so we called the observers almost finite-time. A global and a local result are given in accordance of the type of the considered nonlinearities. We applied the results to a model of a pendulum with friction, and to dynamics with Lotka-Volterra nonlinearities.

In [33], we designed a reduced order observer for nonlinear dynamics. When continuous output measurements are available, we proved that our observers converge in a fixed finite time in the absence of perturbations, and we prove a robustness result under uncertainties in the output measurements and in the dynamics, which bounds the observation error in terms of bounds on the uncertainties. The observers contain a dynamic extension with only one pointwise delay, and they use the observability Gramian to eliminate an invertibility condition that was present in earlier finite time observer designs. We also provided analogs for cases where the measurements are only available at discrete times. We illustrated the advantages of our new observers using a DC motor dynamics

In [46], we provided a new class of finite-time observers for continuous-time nonlinear systems that are affine in the unmeasured state variable and that also contain unknown constant parameters. Our method provides exact values of the state variables and of the constant parameters, in a fixed finite time. We also provided analogs where there is a known delay in the measurements, and for discrete-time systems. Our example illustrates the ease with which our assumptions can be verified in practice.

6.11 Mean field games

Mean field games with free final time

Participants: Romain Ducasse *(LJLL, Université de Paris)*, Guilherme Mazanti *(DISCO)*, Saeed Sadeghi Arjmand *(DISCO)*, Filippo Santambrogio *(Institut Camille Jordan, Université Claude Bernard - Lyon 1)*.

Mean field games are useful models for the evolution of populations of a very large number of indistinguishable rational agents in interaction. Most of the literature on this subject concerns games in a fixed time interval $[0, T]$, i.e., all agents of the game evolve in the same time interval, and they all start and stop their motions at the same time. However, in several situations of practical interest, such as in economics or in crowd motion, agents may be able to leave the game at different times, and this was the major motivation of works studying mean field games with free final time, such as [83, 88], in which time is actually an important part of the optimization criterion of each agent.

The article [19] is the stochastic counterpart of [88]: in both articles, agents evolve in a bounded domain and wish to reach the boundary of the domain in minimal time while having their maximal deterministic velocity upper bounded by a function of their position and the distribution of agents. However, in the latter article, the dynamics of each agent is assumed to be purely deterministic, while the former article also includes an additive Brownian motion in the dynamics of each agent. The stochastic setting prevents the application of the techniques used in the deterministic one, and the strategy of [19] is based instead on a fine analysis of the forward-backward system of coupled parabolic partial differential equations describing equilibria of the game. In addition to existence of equilibria, [19] also addresses their long-time behavior.

The article [38] generalizes the model of [88] to the case of several populations evolving in a non-compact space. While the presence of several populations brings no theoretical difficulty in the analysis, noncompactness requires extra caution, and the main results of the paper are obtained thanks to bounds on the exit time of an agent given their initial position. These bounds also allow one to provide explicit convergence rates of the distribution of agents to their limit configuration. In addition, characterization of equilibria through a system of partial differential equations is achieved without relying on semiconcavity properties of the value function of the optimal control problem underlying the choice of each agent, and requires no more than Lipschitz continuous assumptions on the dynamics of each agent. This is possible thanks to a weak characterization of optimal controls, based on a notion of "direction of maximal descent" which generalizes the notion of "opposite direction to the gradient" to nonsmooth functions.

The presence of state constraints brings major difficulties in the analysis of optimal control problems and mean field games, since they typically break down the semiconcavity of the corresponding value function, which is usually a key property for showing regularity of optimal trajectories and controls and providing a closed-loop characterization of optimal controls. Inspired by the weak characterization of optimal controls from [38] not relying on semiconcavity, the work [39] studies mean field games with state constraints. Using a penalization technique of the optimal control problem inspired from that of [80], [39] proves that optimal controls are Lipschitz continuous and optimal trajectories are C^1. Then, adapting the techniques from [38], the work [39] characterizes optimal controls, establishing thus that equilibria of the corresponding mean field game satisfy a system of partial differential equations.

Numerical aspects of second-order potential mean-field games

Participants: Frédéric Bonnans *(DISCO)*, Pierre Lavigne *(Institut Louis Bachelier)*, Kang Liu *(DISCO)*, Laurent Pfeiffer *(DISCO)*.

The preprints [72] and [65] deal with potential MFGs: they are MFGs equivalent to a convex optimal control problem involving the Fokker-Planck equation, referred to as the potential problem. Our two preprints focus on second-order models consisting of coupled parabolic PDEs (Hamilton-Jacobi and Fokker-Planck). We show in [65] that the generalized conditional gradient (GCG) method can be applied to the potential problem. The method boils down to a sort of fixed point iteration algorithm which is very natural in the context of MFGs, and which generalizes the method of [81]. We further show the linear convergence of the method, under suitable regularity assumptions. Numerical results illustrate the theoretical findings. To our knowledge, no other method of the literature achieves such a speed of convergence.

We introduce in [65] a new discretization method for the resolution of MFGs, based on the theta-scheme and finite differences. It uses a splitting approach that allows to treat the (difficult) nonlinear terms with explicit computations. Moreover, we prove explicit error estimates for the numerical scheme, of order h^r, where h denotes the space parametrization parameters and where $r \in (0,1)$ is related to the regularity of the data of the problem. The available literature for similar schemes has only demonstrated the convergence of the scheme, without explicit rate. A key aspect of the proof is a stability study, which was developed in [72].

We will show in some ongoing work a mesh-independence principle for our theta-scheme: more specifically, we show that the efficiency of the GCG method is not impacted by the smallness of discretization parameters, contrary to other methods of the literature (such as primal-dual methods for example, see [76]). In another direction, we may also address the resolution of non-convex potential MFGs with the GCG method, such as the MFGs with pairwise interactions investigated in the PhD thesis of Saeed Sadeghi Arjmand.

6.12 Study of SIR models

Participants: Frédéric Mazenc, Michael Malisoff *(LSU)*, Hiroshi Ito *(Kyushu Institute)*.

In the paper [21], we studied the stability of a model of susceptible, infected, and recovered (or SIR) disease that includes quarantine of infected individuals and mass vaccination. We proposed a global strict Lyapunov function construction to design feedback controls to asymptotically stabilize a desired endemic equilibrium, and to prove a robustness result of 'input-to-state stability' type for the dynamics with a suitable restriction on the disturbances. Simulations have been carried out to illustrate the potential of the proposed feedback controls to reduce peak levels of infected individuals.

6.13 Attitude stabilization problem

Participants: Frédéric Mazenc, Andrew Miller *(Univ. of Texas)*, Maruthi Akella *(Univ. of Texas)*.

In [48], we solved the attitude stabilization problem for fractionated space systems where the onboard computers cannot run continuously. An auxiliary filter is constructed to imitate the intermittent computer or state acquisition of a small size, power, and weight constrained spacecraft such a CubeSat. The proposed controller does not require angular rate or inertia knowledge and guarantees attitude stabilization and boundedness for all closed loop signals for persistently excited gains driving the auxiliary filter. We have constructed a novel Lyapunov function to guarantee stability including auxiliary functions for strictification of the controller.

6.14 Energy applications: flexibility management

Participants: Frédéric Bonnans *(DISCO)*, Kang Liu *(DISCO)*, Thibault Moquet *(DISCO)*, Laurent Pfeiffer *(DISCO)*, Nadia Oudjane *(EDF R&D)*, Cheng Wan *(EDF R&D)*.

We investigate in [68] a general class of large-scale and nonconvex optimization problems, involving an aggregative term. This term can be interpreted as the sum of the contributions of N agents to some common good, with N large. These problems are motivated by applications in energy management, when many flexibilities are involved. They are small storage devices which can be used to facilitate the integration of volatile renewable energy sources. At a theoretical level, we proved that when N is large, the problem is well approximated by a convex problem, formulated on sets of probability measures. We propose a numerical method based on the Frank-Wolfe algorithm, relying of parallelizable resolutions of subproblems associated with each agent. We demonstrate global estimates of optimality for the output of the method after a given number of iterations. Numerical results on a toy example confirm the efficiency of the method, which outperforms commercial solvers for large values of N.

6.15 Biomechanical application: Modelling the central nervous system action

Participants: Amina Benarab *(DISCO)*, Islam Boussaada *(DISCO)*, Silviu Niculescu *(DISCO)*, Ali El Ati *(IPSA)*, Tamas Insperger *(BME)*, Csenge Molnar *(BME)*, Karim Trabelsi *(IPSA)*.

In [59], we investigate the human quiet stance regulation problem using a single-link inverted pendulum model in the sagittal plane via the ankle joint's passive/active torques' actions. The active torque consists of ankle muscle contractions that are activated by the delayed action of the Central Nervous System (neural controller). The passive torque is related to the intrinsic mechanical properties of the muscle-tendon-ligament component. The failure of the human quiet stance is then directly related to the failure of one or both types of torques. We propose to model the neural controller as a delayed Proportional-Derivative-Acceleration controller acting on the ankle joint's angular position. By using the multiplicity-induced-dominancy property, the critical time delay of the motor control and the critical ankle-joint stiffness are both investigated.

In [42] we consider the stabilization of a rolling balance board by means of the multiplicity-induceddominancy property. A two degree-of-freedom mechanical model of a human balancing on a rolling balance board is analyzed in the sagittal plane. The human body is modeled by an inverted pendulum which connects to the balance board through the ankle joint. The system is stabilized by the ankle torque managed by the central nervous system (CNS). The action of the CNS is modeled by a delayed full state feedback: a pointwise delay stands for all latencies in the neuromechanical system (reaction time, neuromechanical lag, etc.), achieving a good occurrence in terms of the decay rate, it shows the links with dominancy and with the exponential stability property of the solution.

6.16 Mechatronic application: Visual control of UAV

Participants: Amina Benarab *(DISCO)*, Islam Boussaada *(DISCO)*, José Castillo-Zamora *(DISCO)*, Juan Escareno *(Xlim)*.

We have exploited the effects of time-delays on the stability of Unmanned Aerial Vehicles (UAVs). In this regard, the main contribution is a symbolic/numeric application of the Multiplicity-Induced-Dominancy (MID) property in the control of UAVs rotorcrafts featuring time-delays. The MID property is considered to address two of the most representative aerial robotic platforms: a classical quadrotor vehicle and a quadrotor vehicle endowed with tilting-rotors. The aforementioned property leads to an effective delayed feedback control design (MID tuning criteria), allowing the system to meet prescribed behavior conditions based on the placement of the rightmost root of the corresponding closed-loop characteristic function/quasipolynomial. Lastly, the results of detailed numerical simulations, including the linear and non-linear dynamics of the vehicle, are presented and discussed to validate the proposal.

7 Partnerships and cooperations

7.1 International initiatives

7.1.1 STIC/MATH/CLIMAT AmSud projects

TOMENADE

Participants: Frédéric Mazenc.

Title: Topological Methods and Non Autonomous Dynamics for Delay Differential Equations

Program: MATH-AmSud

Duration: January 1, 2021 – December 31, 2022

Local supervisor: Mostafa Adimy

Partners:

- Universidad Tecnologica Metropolitana
- *Pierluigi Benevieri, Universidade de Sao Paulo* (Brasil)

Inria contact: Mostafa Adimy

Summary:

This project addresses open problems about non autonomous systems of Delay Differential Equations modeling some phenomena from life sciences, namely, a metapopulations version of the Nicholson equations and models of competition in a stirred chemostat. Nevertheless, the ideas and methods could be certainly extended in several ways, and we also expect to make progress in topics as the (non autonomous) topological linearization problem and the possibility of converse results for persistence.

Project approved in 2022

NetConHybSDP

Title: Networked control of hybrid systems by semidefinite programming with applications in industry 4.0

Program: STIC-AmSud

Duration: January 1, 2023 – December 31, 2024

Local supervisor: Giorgio Valmorbida

Partners:

- Universidad de Talca (Chile)
- Universidad de Concepcion (Chile)
- Universidad O'Higgins (Chile)
- UNICAMP (Brazil)
- UFRGS (Brazil)
- CEFET-MG (Brazil)

Inria contact: Giorgio Valmorbida

Summary: *This project focuses on stability analysis, control and estimator design for hybrid systems operating in Industry 4.0 networks. The aim is to develop methods and algorithms that are able to cope with challenges such as fault detection, monitoring, effects of sampling, quantization, limitations of bandwidth and signal magnitude, presence of uncertainties, time-delays, nonlinear behaviors and packet losses. In the search for nonconservative results, semidefinite programming tools, that can be accurately and efficiently solved, are used.*

7.2 International research visitors

7.2.1 Visits of international scientists

Other international visits to the team

Jaqueline Godoy Mesquita

Status: Invited professor

Institution of origin: Universidade de Brasília

Country: Brazil

Dates: October 3, 2022 – November 4, 2022

Context of the visit: Jaqueline Godoy Mesquita works on time-delay systems with varying delays, which can be both time- or state-dependent. Her visit to our team is part of an ongoing collaboration to investigate the effects of varying delays on the asymptotic and exponential stability of time-delay systems.

Mobility program/type of mobility: Research stay funded by CentraleSupélec

Guilherme Mazanti

Visited institution: Justus-Liebig-Universität Gießen

Country: Germany

Dates: March 14, 2022 – March 18, 2022

Context of the visit: The main purpose of this one-week stay was to continue a collaboration with Jaqueline Godoy Mesquita (who was spending a sabbatical year at Justus-Liebig-Universität Gießen at the time) on time-delay systems with varying delays.

Mobility program/type of mobility: Research stay funded by the Justus-Liebig-Universität Gießen

7.3 National initiatives

We are members of the ANR Dreamy

7.4 Regional initiatives

Laurent Pfeiffer chairs the PGMO (programme d'optimisation Gaspard Monge) project "Large-scale and non-convex multi-agent optimization for energy management" (other DISCO participants: Frédéric Bonnans, Kang Liu, and Thibault Moquet). Industrial partners: Nadia Oudjane (EDF R&D) and Cheng Wan (EDF R&D). Funding in 2022: 7000 euros.

8 Dissemination

8.1 Promoting scientific activities

8.1.1 Scientific events: organisation

General chair, scientific chair

- Islam Boussaada is the chair of the working group OSYDI of the *SAGIP*, on average two per year.
- Guilherme Mazanti was organizer of the workshop *Contrôle des EDPs : approches en mathématique et en automatique*, held in Paris, France, on November 2–3, 2022.
- Guilherme Mazanti is organizer of the *Séminaire d'Automatique du Plateau de Saclay*, held in Gif-sur-Yvette, France, on average once per month.

Member of the organizing committees

- Guilherme Mazanti and Laurent Pfeiffer were members of the organizing committee of the 27th International Conference on Difference Equations and Applications (ICDEA 2022), held in CentraleSupélec in Gif-sur-Yvette, France, on July 18–22, 2022.
- Laurent Pfeiffer was member of the organizing committee of the 18th IFAC Workshop on Control Applications of Optimization.

Minisymposium organization

- Islam Boussaadaorganized an invited session on pole placement methods in time delay systems during he 17th IFAC workshop on Time-delay Systems, September 27-30, Montréal, CA
- Guilherme Mazanti and Laurent Pfeiffer organized a minisymposium on mean-field games and control during the PGMO days (December 2022, EDF-Lab).
- Laurent Pfeiffer organized a minisymposium on optimal control, jointly with Riccardo Bonalli (CNRS, L2S), during the 18th IFAC Workshop on Control Applications of Optimization (July 2022, CentraleSupélec).

8.1.2 Scientific events: selection

- Catherine Bonnet was SIAM Associate Editor of the 2022 American Control Conference, held in Atlanta, USA, on June 8-10, 2022.
- Islam Boussaada was Associate Editor of the 17th IFAC Workshop on Time Delay Systems, Montreal, CA, on September 27-30, 2022.
- Frederic Mazenc was Associate Editor of the European Control Conference, London, UK (2022).

Member of the conference program committees

- Catherine Bonnet, Islam Boussaada, Guilherme Mazanti, Frederic Mazenc, and Silviu-Iulian Niculescu were members of the international program committee of the 17th IFAC Workshop on Time Delay Systems (TDS 2022), held in Montreal, Canada, on September 27–30, 2022.
- Catherine Bonnet was member of the international program committee of the 25th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2022), help in Bayreuth, Germany, on September 12–16 2022.
- Fédéric Mazenc was member of the program committee of the 2022 American Control Conference, held in Atlanta, USA, on June 8-10, 2022.
- Fédéric Mazenc was member of the program committee of 14th IFAC International Workshop on Adaptive and Learning Control Systems, June 29th-July 1st Casablanca, Morroco.
- Fédéric Mazenc was member of the International Program Committee of the International Conference on Systems and Control, November 23-25 2022, Marseille, France.

8.1.3 Journal

Member of the editorial boards

- Guilherme Mazanti is member of the editorial board of the journal *Matemática Contemporânea*.
- Frederic Mazenc is associate editor of the journal *IEEE Control Systems Letters*.
- Frederic Mazenc is editor of the journal *Asian Journal of Control*.
- Giorgio Valmorbida is member of the editorial board of the journal *IMA Journal of Mathematical Control and Information*.
- Giorgio Valmorbida is member of the editorial board of the journal *Journal of Control, Automation and Electrical Systems*.

8.1.4 Invited talks

- Guilherme Mazanti was invited to give a talk in the workshop *Analysis and Control of (bi)linear PDEs*, held in Rome, Italy, on September 7–9, 2022.
- Laurent Pfeiffer was invited to give a talk at the SIAM Conference on Analysis of Partial Differential Equations (March 2022, online), at the Workshop on Mathematical Data Science, Control and Optimization (October 2022, Graz, Austria), and at the Inauguration de la Fédération de Mathématiques de CentraleSupélec (November 2022, CentraleSupélec).

8.1.5 Scientific expertise

- Catherine Bonnet is a member of the Scientific Council of CentraleSupélec since December 2021, of the Inria Evaluation Committee since 2015.
- Islam Boussaada is a member of the Scientific Council of TéSA cooperative research laboratroy, Toulouse, since June 2021.

8.1.6 Research administration

- Catherine Bonnet is a member of the : - Parity Committee of Inria created since its creation in 2015. - Bureau du Comité des Equipes Projets du CRI Saclay-Ile-de-France since 2018. - Coordination committee of the Mentoring Program of Inria Saclay-Île-de-France. She is the co-President of the Parity Committee at Inria since January 2022. She is the Parity Referent at L2S for CNRS since its creation in November.
- Islam Boussaada is a member of the administration council of the SAGIP association.
- Frederic Mazenc is membre of the "Commission de Développement Technologique".
- Laurent Pfeiffer is correspondent for the hiring mission (mission recrutement) at Inria-Saclay.
- Giorgio Valmorbida is member of the "Conseil de Laboratoire" of the L2S

8.2 Teaching - Supervision - Juries

8.2.1 Teaching

- Licence: Islam Boussaada, *Complex and harmonic analysis*, 127h, 1st year, IPSA, France.
- Licence: Guilherme Mazanti, *Partial differential equations*, 16.5h, 1st year, CentraleSupélec, Université Paris-Saclay.
- Licence: Silviu Niculescu, *Mathematics*, 15h, 1st year, ENSMP Paris, France.
- Licence: Silviu Niculescu, *Introduction to optimization*, 30h, 1st year, ESIEE Paris, France.
- Licence: Giorgio Valmorbida, *Signal Processing*, 1st year, 43h CentraleSupélec Université Paris-Saclay.
- Master: Silviu Niculescu, *Signals and Systems*, 12h, ESIEE Paris, France.
- Master: Giorgio Valmorbida, *Control*, 40.5, Master MAE (M1), Université Paris-Saclay.
- Master: Giorgio Valmorbida, *Stability of Dynamical Systems*, Master ATSI (M2), Université Paris-Saclay.
- Master: Guilherme Mazanti, *Optimization*, 46h, 2nd year, CentraleSupélec, Université Paris-Saclay.
- Master: Laurent Pfeiffer, *Optimal control of ordinary differential equations*, 15h, Optimization Master, Université Paris-Saclay and Ensta-Paris
- Master: Laurent Pfeiffer, *Continuous optimization*, 18h, Energy Master, Institut Polytechnique de Paris and Ensta-Paris
- Master: Laurent Pfeiffer, *Optimization project*, 18h, Energy Master, Institut Polytechnique de Paris and Ensta-Paris
- Master: Giorgio Valmorbida, *Optimization*, 2nd year, 43h CentraleSupélec Université Paris-Saclay.
- Master: Giorgio Valmorbida, *Hybrid Systems*, 3rd year, 18h CentraleSupélec Université Paris-Saclay.
- Master: Giorgio Valmorbida, *Control*, , 2nd years, 55.5h, CentraleSupélec Université Paris-Saclay.

- Master: Giorgio Valmorbida, *Projects and Internship supervision*, 2nd and 3rd years, 81h, CentraleSupélec Université Paris-Saclay.
- Master: Giorgio Valmorbida, *Nonlinear Systems*, 3h, CentraleSupélec Executive Education, Université Paris-Saclay.
- Doctorat: Silviu Niculescu, *Controlling Delayed Dynamics: Advances in Theory, Methods and Applications*, 7h, CISM Udine, Italy.

8.2.2 Supervision

PhD theses defended in 2022:

- Amina Benarab
  - Supervisors: Catherine Bonnet, Islam Boussaada and Karim Trabelsi
  - Thesis title: Contribution to the partial pole placement problem for some classes of time-delay systems with applications
  - Defended November 30th 2022
  - Funding: IPSA
- Ali Diab
  - Supervisors: William Pasillas-Lepine et Giorgio Valmorbida
  - Thesis title: Stability analysis and control design for time-delay systems with applications to automotive steering systems
  - Started in 2019
  - Funding: MESRI.

Ongoing PhD theses:

- Kang Liu
  - Supervisors: Laurent Pfeiffer and Frédéric Bonnans
  - Thesis title: Mean-field optimal control and applications in flexibility management
  - Started in 2020
  - Funding: AMX fellowship.
- Thibault Moquet
  - Supervisors: Guilherme Mazanti and Laurent Pfeiffer
  - Thesis title: Mean field games: potential games and duality methods
  - Started in 2022
  - Funding: Labex Mathématique Hadamard.
- Saeed Sadeghi Arjmand
  - Supervisors: Anne-Sophie De Suzzoni and Guilherme Mazanti
  - Thesis title: Mean field games with free final time
  - Defended December 9th 2022
  - Funding: École Doctorale de Mathématiques Hadamard (EDMH), Université Paris-Saclay

Master's theses:

- Thibault Moquet (Optimization Master, Université Paris-Saclay)
  - Supervisor: Laurent Pfeiffer
  - Thesis title: Aggregative nonconvex optimization: Two dual-based numerical methods
  - Funding: Programme Gaspard Monge d'Optimisation (PGMO).

8.2.3 Juries

- Catherine Bonnet was a member of several recruiting committees at Inria (Bordeaux young researchers competition, young researchers with disabilities competition, Senior researcher competition, Rennes Chair of Junior Professor competition). She was also a member of the Lecturer recruiting committee of Université d'Evry Val d'Essonne.
- Catherine Bonnet was a member of the PhD committee of Grace Younès, Sorbonne Université; of Ronald Manriquez Penafiel université Paris-Saclay; of Wenjie Wei, université de Lille and of Vincent Tartaglione, universiité de Bordeaux. She was also of member of the HDR committee of Dayan Liu, INSA Val de Loire.
- Islam Boussaada was a member of the PhD committee of Sijia Kong, Ecole des Mines Paris; of Alexandre Rigaud université Poitiers;
- Giorgio Valmorbida was a member of the PhD panel of Daniel DENARDI HUFF, Université de Grenoble Rhone Alpes; was a referee (rapporteur) and member of the PhD panel of Tanguy SIMON, Université de Lyon.

8.3 Popularization

8.3.1 Interventions

Catherine Bonnet participated to the program « 1 scientifique, 1 classe : Chiche » and gave two 1h30 talks at Lycée Hoche, Versailles.

9 Scientific production

9.1 Major publications

[1] C. Bonnet and J. Partington. 'Stabilization of some fractional delay systems of neutral type'. In: *Automatica* 43 (2007), pp. 2047–2053.

[2] C. Bonnet, A. R. Fioravanti and J. R. Partington. 'Stability of Neutral Systems with Commensurate Delays and Poles Asymptotic to the Imaginary Axis'. In: *SIAM Journal on Control and Optimization* 49.2 (Mar. 2011), pp. 498–516. URL: https://hal.inria.fr/hal-00782325.

[3] I. Boussaada, I.-C. Morarescu and S.-I. Niculescu. 'Inverted pendulum stabilization: characterization of codimension-three triple zero bifurcation via multiple delayed proportional gains'. In: *Systems Control Lett.* 82 (2015), pp. 1–9.

[4] M. Malisoff and F. Mazenc. *Constructions of Strict Lyapunov Functions*. Communications and Control Engineering Series. Springer-Verlag London Ltd., 2009.

[5] F. Mazenc, M. Malisoff and S.-I. Niculescu. 'Reduction Model Approach for Linear Time-Varying Systems with Delays'. In: *IEEE Transactions on Automatic Control* 59.8 (2014), pp. 2068–2014.

[6] W. Michiels and S.-I. Niculescu. *Stability, Control, and Computation for Time-Delay Systems*. Ed. by S.-I. Niculescu and W. Michiels. Philadelphia, PA: Society for Industrial and Applied Mathematics, 2014.

[7] S.-I. Niculescu. *Delay Effects on Stability: a Robust Control Approach*. Vol. 269. Lecture Notes in Control and Information Sciences. Springer, 2001.

[8] I. Queinnec, S. Tarbouriech, G. Valmorbida and L. Zaccarian. 'Design of Saturating State-Feedback with Sign-Indefinite Quadratic Forms'. In: *IEEE Transactions on Automatic Control* (2021). DOI: 10.1109/TAC.2021.3106878. URL: https://hal.laas.fr/hal-03353776.

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[10] G. Valmorbida, M. Ahmadi and A. Papachristodoulou. 'Stability Analysis for a Class of Partial Differential Equations via Semidefinite Programming'. In: *IEEE Transactions on Automatic Control* 61.6 (June 2016), pp. 1649–1654.

[11] G. Valmorbida, S. Tarbouriech and G. Garcia. 'Design of Polynomial Control Laws for Polynomial Systems Subject to Actuator Saturation'. In: *IEEE Transactions on Automatic Control* 58.7 (July 2013), pp. 1758–1770.

[12] G. Valmorbida and F. Ferrante. 'On Quantization in Discrete-Time Control Systems: Stability Analysis of Ternary Controllers'. In: *CDC 2020 - 59th IEEE Conference on Decision and Control*. IEEE. Jeju Island (virtual), South Korea, Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03092417.

9.2 Publications of the year

International journals

[13] J. Auriol, I. Boussaada, R. J. Shor, H. Mounier and S.-I. Niculescu. 'Comparing advanced control strategies to eliminate stick-slip oscillations in drillstrings'. In: *IEEE Access* 10 (2022), pp. 10949–10969. DOI: 10.1109/ACCESS.2022.3144644. URL: https://hal.science/hal-03530284.

[14] A. Benarab, I. Boussaada, K. Trabelsi and C. Bonnet. 'Multiplicity-Induced-Dominancy property for second-order neutral differential equations with application in oscillation damping'. In: *European Journal of Control* (2022). DOI: 10.1016/j.ejcon.2022.100721. URL: https://hal.science/hal-03626756.

[15] A. Bertolin, R. Oliveira, G. Valmorbida and P. Peres. 'Control design of uncertain discrete-time Lur'e systems with sector and slope bounded nonlinearities'. In: *International Journal of Robust and Nonlinear Control* (17th May 2022). DOI: 10.1002/rnc.6181. URL: https://hal.science/hal-03685125.

[16] F. Bonnans, G. Bonnet and J.-M. Mirebeau. 'A linear finite-difference scheme for approximating Randers distances on Cartesian grids'. In: *ESAIM: Control, Optimisation and Calculus of Variations* 28 (2022). DOI: 10.1051/cocv/2022043. URL: https://hal.science/hal-03125879.

[17] I. Boussaada, G. Mazanti and S.-I. Niculescu. 'The generic multiplicity-induced-dominancy property from retarded to neutral delay-differential equations: When delay-systems characteristics meet the zeros of Kummer functions'. In: *Comptes Rendus. Mathématique* 360 (2022), pp. 349–369. DOI: 10.5802/crmath.293. URL: https://hal.science/hal-03298718.

[18] J. d. J. Castillo-Zamora, I. Boussaada, A. Benarab and J. Escareno. 'Time-Delay Control of Quadrotor Unmanned Aerial Vehicles: A Multiplicity-Induced-Dominancy Based Approach'. In: *Journal of Vibration and Control* (21st May 2022). DOI: 10.1177/10775463221082718. URL: https://hal.science/hal-03561999.

[19] R. Ducasse, G. Mazanti and F. Santambrogio. 'Second order local minimal-time Mean Field Games'. In: *Nonlinear Differential Equations and Applications* 29 (27th Apr. 2022), Paper No. 37, 32 pp. DOI: 10.1007/s00030-022-00767-2. URL: https://hal.science/hal-02616965.

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[21] H. Ito, M. Malisoff and F. Mazenc. 'Strict Lyapunov functions and feedback controls for SIR models with quarantine and vaccination'. In: *Discrete and Continuous Dynamical Systems - Series B* 27.12 (Dec. 2022), pp. 6969–6988. DOI: 10.3934/dcdsb.2022029. URL: https://hal.inria.fr/hal-03890647.

[22] A. Le Rhun, J. F. Bonnans, G. de Nunzio, T. Leroy and P. Martinon. 'A Bilevel Energy Management Strategy for HEVs Under Probabilistic Traffic Conditions'. In: *IEEE Transactions on Control Systems Technology* 30.2 (Mar. 2022), pp. 728–739. DOI: 10.1109/TCST.2021.3073607. URL: https://hal-ifp.archives-ouvertes.fr/hal-03608048.

[23] F. Mazenc and M. Malisoff. 'Feedback Stabilization and Robustness Analysis using Bounds on Fundamental Matrices'. In: *Systems and Control Letters* (2022). URL: https://hal.inria.fr/hal-03891450.

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[25] F. Mazenc and M. Malisoff. 'New Bounds for State Transition Matrices'. In: *IEEE Control Systems Letters* (2022). URL: https://hal.inria.fr/hal-03891408.

[26] F. Mazenc and M. Malisoff. 'New Versions of Halanay's Inequality with Multiple Gain Terms'. In: *IEEE Control Systems Letters* (2022). DOI: 10.1109/LCSYS.2021.3133214. URL: https://hal.inria.fr/hal-03711601.

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