RESEARCH CENTRE

Saclay - Île-de-France

IN PARTNERSHIP WITH:

CNRS, CentraleSupélec

2021

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

Contents

Project-Team DISCO

Creation of the Project-Team: 2012 January 01

Keywords

Computer sciences and digital sciences

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.1.3. – Discrete Modeling (multi-agent, people centered)

A6.4.1. – Deterministic control

A6.4.3. – Observability and Controlability

A6.4.4. – Stability and Stabilization

Other research topics and application domains

B2.5. – Handicap and personal assistances

B3.6. – Ecology

B5.2.3. – Aviation

B7.2.1. – Smart vehicles

1 Team members, visitors, external collaborators

Research Scientists

- Catherine Bonnet [Team leader, Inria, Senior Researcher, HDR]
- Joseph Frederic Bonnans [Inria, Senior Researcher, from Sep 2021, HDR]
- Guilherme Mazanti [Inria, ISFP]
- Frédéric Mazenc [Inria, Senior Researcher, HDR]
- Silviu-Iulian Niculescu [CNRS, Senior Researcher, HDR]
- Laurent Pfeiffer [Inria, Researcher, from Sep 2021]

Faculty Members

- Islam Boussaada [IPSA, Professor, HDR]
- Giorgio Valmorbida [Centrale-Supélec, Associate Professor]

Post-Doctoral Fellow

- Sébastien Fueyo [Centrale-Supélec, until Aug 2021]

PhD Students

- Amina Benarab [Univ Paris-Saclay]
- Guillaume Bonnet [Univ Paris-Saclay, from Sep 2021]
- Jose De Jesus Castillo Zamora [Univ Paris-Saclay, until Aug 2021]
- Ali Diab [Univ Paris-Saclay]
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- Pierre Lavigne [École polytechnique, from Sep 2021]
- Kang Liu [École polytechnique, from Sep 2021]
- Alejandro Martinez Gonzalez [Centrale-Supélec, until Jun 2021]
- Javier Pereyra Zamudio [Institut Polytechnique National de Mexico - Mexique, until Aug 2021]
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Interns and Apprentices

- Ayrton Hammoumou [Inria, Jun 2021]
- Jayvir Raj [Inria, from Jun 2021 until Aug 2021]

Administrative Assistant

- Irina Lahaye [Inria]

External Collaborator

- Ali Zemouche [Univ de Lorraine, until Sep 2021, 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 these limitations 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. These constraints appear as nonlinearities as saturation and quantization in 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], [89].

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 is 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 of the system parameters such as road and vehicle conditions.

5 Highlights of the year

5.1 Awards

Jeanne Redaud got the Best Student Paper Award, 16th IFAC Workshop on Time-Delay Systems, Guangzhou, China, September 29 - October 01 2021.

6 New software and platforms

6.1 New software

6.1.1 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

Contact: Islam Boussaada

Partners: Cyb'Air-IPSA, ICODE, CentraleSupélec

7 New results

7.1 Partial pole placement techniques for time-delay systems

Participants: Islam Boussaada, Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Sébastien Fueyo, Adrien Leclerc *(IPSA, France)*, Xu-Guang Li *(Northeastern University, China)*, Guilherme Mazanti, César-Fernando Méndez-Barrios *(UASLP, Mexico)*, Silviu-Iulian Niculescu, Max Perraudin *(IPSA, France)*, Jayvir Raj *(IPSA, France)*.

Exploring some previous ideas present, e.g., in [90], the seminal works [79, 80] highlighted the fact that spectral values of time-delay systems attaining their maximal possible multiplicity tend to be dominant, in what came to be known as the *multiplicity-induced-dominancy* (MID) property. The MID property turns out to be a very important tool in designing low-complexity feedback control laws for time delay-systems. Since these seminal works, a lot of research effort has been put into the characterization of the classes of systems for which such a property holds and exploring it in applications for stabilizing time-delay systems.

The most general result so far involving the MID property is the one from [17], which shows that the MID property holds for retarded and neutral time-delay systems of an arbitrary order with a single delay and highlights the applicability of such a property in the design of stabilizing feedback laws. Such results are obtained by exploring links, previously highlighted in [25] for a particular class of systems and then generalized in [17], between spectra of time-delay systems and roots of a family of confluent hypergeometric functions, known as *Kummer functions*.

Thanks to such links, results on the location of roots of Kummer functions are crucial for the stability analysis of time-delay systems. However, there is an important lack of results in this sense in the literature. Early results by G. E. Tsvetkov obtained in the 1940's (see [92, 91]) turned out to be incorrect: in addition to providing counterexamples to a result in [92], the paper [16] by members of the DISCO team provided corrected versions of Tsvetkov's statements along with their proof, which is based on Hille's method described in [84].

Most of the literature on the MID property has considered only systems with a single delay. The recent work [46] is among the few exceptions and considers the MID property for a first-order system of retarded type with two delays. By considering the ratio between the smallest and the largest delay as a parameter, [46] 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 such a class of systems.

Partial pole placement methods for time-delay systems are implementend in the DISCO Team software P3δ, and the paper [43] provides a description of the features recently implemented in the software, including the possibility of plotting admissibility regions and stabilization techniques based on the coexisting-real-roots-induced-dominancy (CRRID) property.

A summary of several partial pole placement techniques for the stabilization of time-delay systems was presented in the tutorial paper [58], which collects and details several recent results by the authors on the topic, completing them with as many illustrative applications.

7.2 Multiplicity-induced-dominancy

Participants: Jean Auriol *(L2S, CNRS)*, Amina Benarab, Catherine Bonnet, Islam Boussaada, Guilherme Mazanti, Hugues Mounier *(L2S, CentraleSupélec)*, Silviu-Iulian Niculescu, Karim Trabelsi *(IPSA)*.

The work [49] has explored the MID property in the context of delay differential-algebraic systems, whose motivation come from the study of some lossless hyperbolic partial differential equations appearing in the modeling of electric circuits involving transmission lines. The main results of [49] establish the MID property for such a model as well as for scalar first-order neutral delay equations.

In [39] a control-oriented model of torsional vibrations occurring in rotary oil-well drilling process is proposed. Such vibrations are known to constitute an important source of economic losses; drill bit wear, pipe disconnection, borehole disruption and prolonged drilling time, among other consequences. More precisely, torsional vibrations are assumed to be governed by a wave equation with weak damping term. An appropriate stabilizing controller with a reduced number of parameters is proposed for damping such torsional vibrations. Such a controller allows further exploration of the effect of multiple roots with maximal admissible multiplicity for linear neutral systems with a single delay. The MID-based design is further exploited to quench the torsional vibrations along the rotary drilling system. The proposed control law guarantees the existence of robustness margins with respect to delays and parameters uncertainties.

7.3 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.

7.4 Stability analysis of partial differential equations modelling propagation phenomena

Participants: Islam Boussaada, Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Swann Marx *(LS2N, CNRS, France)*, Guilherme Mazanti, Silviu-Iulian Niculescu.

Propagation of mass, energy, or information can generally be modelled by partial differential equations, in particular equations of hyperbolic type such as wave, transport, telegrapher, or Saint-Venant equations, for instance, which is one of the motivations of the stability analysis of such systems. In situations modeling one-dimensional propagation, some of these equations can be reduced to time-delay systems, in which the delays typically represent a propagation time.

In [49], we have exploited this kind of reduction to analyse the stability of electric circuits coupled with a transmission line modelled by a telegrapher equation.

The work [20] considers the case of wave equations with nonlinear boundary conditions, the classes of nonlinearity addressed in the paper being motivated by the practical implementation of feedback control laws. That article provides several stability criteria and characterizes optimal decay rates in terms of the behavior of the nonlinearity.

7.5 Control of interconnected PDEs

Participants: Jean Auriol, Federico Bribiesca Argomedo, Silviu-Iulian Niculescu, Jeanne Redaud.

Networks of interconnected linear partial differential equations (PDEs) represent a class of systems that naturally arise when modeling industrial processes for which the dominant dynamics involve a transport phenomenon. The main idea of the proposed control approach relies on the infinite dimensional “backstepping” method. We studied elementary PDEs systems connected between themselves or with Ordinary Differential Equations, under three main work axis: (i) a recursive dynamics interconnection framework [40], [34] for designing controllers and observers for a chain of PDEs, coupled at one end with a scalar ODE; such an idea was adapted to the control of drilling systems; (ii) second, the use of Fredholm transforms to deal with underactuated systems (control-law at the in-between boundary), with a “time-delay systems” oriented approach [61], and, finally, (iii) a PDE system coupled at both ends with ODEs, using a frequency approach [69].

7.6 Comparison of linear switched systems with deterministic or probabilistic switching

Participants: Yacine Chitour *(L2S, Univ. Paris-Saclay, France)*, Guilherme Mazanti, 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 (see, e.g., [87]). Different measures of stability were proposed in the literature for switched systems, such as joint spectral radii and Lyapunov exponents.

In the work [21], we have compared probabilistic and deterministic measures of stability for discrete-time switched systems, showing that the Markovian switching framework tends to be "more stable" than the deterministic point of view, except in some very particular situations which are completely characterized in the paper and correspond, essentially, to switched systems which can be brought, up to a scaling and a change of variables, to systems determined by orthogonal matrices.

The work [71] is the continuous-time counterpart of [21]. In continuous time, major difficulties appear due to the fact that arbitrarily fast switching may occur both in the determinisitc and in the Markovian switching settings, and one is then brought to analyze the behavior of Markovian processes with fast switching, which is done thanks to nontrivial adaptations of results from various works by C. Landim and collaborators, in particular [86]. Thanks to this analysis, [71] arrives to the conclusion that the Markovian switching framework tends to be "more stable" than the deterministic point of view also in continuous time, except in some very particular situations, which are completely characterized in dimensions 2 and 3. Partial results are also provided in higher dimensions.

7.7 New advances on backstepping

Participants: Frédéric Mazenc, Michael Malisoff *(LSU)*, Sabine Mondie *(CINVESTAV)*, Javier Zamudio *(CINVESTAV)*.

In the paper [54], we develop for time-varying nonlinear systems with delay in the input an alternative approach of the fundamental design of nonlinear control laws called 'backstepping'. It relies on the introduction of artificial delays. The result is applied to a mechanical systems called TORA system.

7.8 Control for discrete-time systems and systems with discrete measurements

Participants: Xuefei Yang *(Harbin Institute)*, Bin Zhou *(Harbin Institute)*, James Lam *(Hong Kong University)*, Michael Malisoff *(LSU)*, Frédéric Mazenc.

In the work [36], we studied the problem of global stabilization of discrete-time linear systems subject to input saturation and time delay using prediction and saturation techniques. Both current and delayed feedback information are utilized in the controller design. Also, we proposeed a systematic control design procedure for globally stabilizing general discrete-time linear systems subject to multiple inputs and/or multiple inputs delays is proposed. In the paper [55], we proved a robust stabilization theorem for systems with time-varying disturbances and sampled measurements, using novel bounds on fundamental matrices for systems with disturbances. Our main tools use properties of positive systems and Metzler matrices.

7.9 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, [30], [56], [57], we addressed the case of continuous-time linear systems, continuous-time linear systems with delay, discrete-time systems. Besides, we considered systems for which only some components of the state variable are available.

7.10 Halanay's inequality

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

We developed in the contributions [31], [32], [52], [53] 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 ODEs in which a time-varying delay is inserted.

7.11 Stability Analysis of Delay Systems with Lyapunov-Krasovskii methods

Participants: Giorgio Valmorbida, Ali Diab *(University of Illinois at Urbana-Champaign)*, 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 literatures in terms of delay margin enlargement. We are currently working towards the extension of these analysis results to the control design problems.

7.12 Stability analysis of Piece-Wise Affine Systems

Participants: Giorgio Valmorbida, Leonardo Broering Groff, Joao Manoel Gomes da Silva Jr *(Universidade Federal do Rio Grande do Sul)*, Francesco Ferrante *(Gipsa-lab)*.

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 developed an event-triggered strategy that also avoids the enumeration and relies on an piece-wise quadratic triggering function. This strategies allow to reduce the number of control action updates.

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.

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 Controle, we obtained solutions to the implicit equation with a speed up factor of 20-100 with respect to a standard QP interior-point solver.

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 they are used in closed loop wit

7.13 Observers

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

In the contributions [27] and [50] we provided novel reduced-order observer designs for continuous-time nonlinear systems with measurement error. Our first result provides observers that converge in a fixed finite time.Our second result applies under discrete measurements, and provides observers that converge asymptotically with a rate of convergence that is proportional to the negative of the logarithm of the size of a sampling interval. We illustrated our observers using a model of a single-link robotic manipulator coupled to a DC motor with a nonrigid joint, and in a pendulum example. In [29] and [51], we provide another type of reduced order observer designs for a class of 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 results using a DC motor dynamics.

7.14 Mean field game models for crowd motion

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

Motivated by modeling, control, and optimization objectives, the mathematical analysis of crowd motion is the subject of a very large number of works from diverse perspectives [83, 88]. The game-theoretical point of view used in mean field game models for crowd motion consists in assuming that each pedestrian in the crowd is a rational agent whose aim is to optimize some objective function which depends on the other agents of the crowd.

The work [72] has adressed the case of stochastic minimal-time mean field games in which agents wish to reach the boundary of a given set in minimal time, but the movement of each agent is submitted to a Brownian motion. The main results of the paper concern the existence of equilibria, characterized as a solution to a system of PDEs, as well as the description of some of its properties, in particular its long-time asymptotic behavior.

In [76], we have considered deterministic minimal-time mean field games in the presence of several interaction populations. In addition to the multi-population setting, the paper also brings the novelty of considering deterministic minimal-time mean field games in unbounded domains, analyzing asymptotic stability of equilibria in this context and, most importantly, providing a weak characterization of optimal choices of agents which does not rely on semiconcavity properties of the value function of the optimal control problem underlying the choice of each agent.

Semiconcavity of the value function of optimal control problems is a key property in order to provide some classical characterizations of optimal controls, but such a property fails to hold in the presence of state constraints. Based on the weak characterization techniques of optimal controls from [76] not relying on semiconcavity, the works [63, 77] have addressed mean field games with state constraints, a longstanding problem in mean field game theory. This problem had previously been addressed for other kinds of mean field games in [81, 82], but the techniques of those references cannot be directly applied to the minimal-time mean field games under consideration in [63, 77].

7.15 Energy

Participants: Frédéric Mazenc, Robert Grino *(Univ. Polit. de Catalunya)*, Romeo Ortega *(ITAM)*, Emilia Fridman *(Tel Aviv Univ.)*, Jin Zhang *(Tel Aviv Univ.)*.

We proposed in [22] a simple dynamic model of. a Constant Power Loads (CPL) that is suitable for the analysis of single-phase AC systems and gave conditions on the tuning gains of the model that guarantee the CPL behavior is effectively captured.

8 Partnerships and cooperations

Participants: Catherine Bonnet, Islam Boussaada, Guilherme Mazanti, Silviu Niculescu.

8.1 International initiatives

8.1.1 STIC/MATH/CLIMAT AmSud project

MathAmsud project TOMENADE, "Topological Methods and Non Autonomous Dynamics for Delay Differential Equations".

8.2 International research visitors

Jaqueline Godoy Mesquita

Status: Professor

Institution of origin: University of Brasília

Country: Brazil

Dates: September 30 – December 6, 2021

Context of the visit: Jaqueline Godoy Mesquita is a specialist on systems on time-scales and time-delay systems, working in particular with state-dependent delays. After initial discussions during a special session organized by J. G. Mesquita and G. Mazanti on time-delay systems in July 2019, discussions have shown potential applications of combinations between techniques developed by J. G. Mesquita and members of the DISCO Team in order to provide new insights and perspectives on the analysis of hybrid systems and of time-delay systems with state-dependent delays. These kind of systems appear naturally when modeling propagation of information on networks, due to the presence of both discrete and continuous dynamics as well as non-constant time-delays. In particular, modeling delays with a state dependence is currently a very hot topic in many applications and J. G. Mesquita is an international expert on the subject. During her visit, new collaborations were established to study relations between several classes of generalized systems, such as systems on time-scales, measure differential equations, and generalized ODEs.

Mobility program/type of mobility: Research stay funded by the DigiCosme LabEx.

8.3 National initiatives

We are members of the ANR Dreamy https://dreamy.run/

9 Dissemination

9.1 Promoting scientific activities

Participants: Catherine Bonnet, Islam Boussaada, Guilherme Mazanti, Frédéric Mazenc, Silviu Niculescu, Giorgio Valmorbida.

9.1.1 Scientific events: organisation

Member of the organizing committees Four members of the team (Islam Boussaada, Guilherme Mazanti, Silviu-Iulian Niculescu, and Giorgio Valmorbida) participated in the organization of the 3rd Workshop on Delays and Constraints on Distributed Parameter Systems (DECOD 2021), which took place in November 23–26, 2021, at CentraleSupélec, Gif-sur-Yvette, France.

9.1.2 Scientific events: selection

Catherine Bonnet was Associate Editor for the American Control Conference, New Orleans (2021).

Frederic Mazenc was Associate Editor for the European Control Conference, Rotterdam, The Netherlands (2021) and the American Control Conference, New Orleans (2021).

Member of the conference program committees

Catherine Bonnet was Member of the program committee and Associate Editor of the 16th IFAC workshop onTime Delay Systems, Guangzhou, China (2021).

Islam Boussaada was Member of the program committee and Associate Editor of the 16th IFAC workshop on Time Delay Systems, Guangzhou, China (2021).

Islam Boussaada is Member of the program committee of the 17th IFAC workshop on Time Delay Systems, Montréal, Canada (2022).

Frederic Mazenc is Member of the program committee of 14th IFAC International Workshop on Adaptive and Learning Control Systems, www.alcos2022.org

Frederic Mazenc is Member of the program committee of the American Control Conference 2022.

Reviewer The team reviewed papers for several international conferences including IEEE Conference on Decision and Control, IEEE American Control Conference, European Control Conference, Mathematical Theory of Networks and Systems ...

9.1.3 Journal

Member of the editorial boards G. Mazanti is Associate Editor of Matemática Contemporânea, published by the Brazilian Mathematical Society.

F. Mazenc was Associate Editor IEEE Control Systems Letters and Editor for the Asian Journal of Control.

Reviewer - reviewing activities The team reviewed papers for several journals including SIAM Journal on Control and Optimization, Automatica, IEEE Transactions on Automatic Control, Systems and Control Letters, IEEE Control Systems Letters ...

9.1.4 Invited talks

Guilherme Mazanti was invited to give several talks in scientific seminars, including the *Online Seminar on Distributed Parameter Systems*, the *CAMP (Computational, Applied Mathematics, and PDE) Seminar* from The University of Chicago, the *Online seminar Control in Times of Crisis*, the online *Seminar on nonlocal systems* and the *Analysis Seminar* at the University of Brasília.

Guilherme Mazanti gave a talk in the special session “Delay and functional differential equations and applications” at the Mathematical Congress of the Americas (MCA) 2021, entitled *The multiplicity-induced-dominancy property for scalar delay-differential equations*.

Guilherme Mazanti participated in a round table on “Mathematical challenges in automation and control” at the Brazilian Symposium on Intelligent Automation (SBAI), and gave a short talk entitled *Control and stabilization of infinite-dimensional systems*.

Frederic Mazenc was plenary speaker of the Third IFAC Conference on Modelling, Identification and Control of Nonlinear Systems 2021. Title of his talk: Two new stability analysis techniques

9.1.5 Leadership within the scientific community

Catherine Bonnet is a member of the IFAC Technical Committees *Distributed Parameter Systems* and *Biological and Medical Systems*.

Islam Boussaada is a member of the IFAC Technical Committees *Linear Control Systems*.

Islam Boussaada is co-leading the national research group *Tools for analysis and synthesis of infinite-dimensional systems* (GT OSYDI) of the SAGIP.

9.1.6 Scientific expertise

Catherine Bonnet is a member of the Scientific Council of CentraleSupélec since December 2021, of the Inria Evaluation Committee since 2015 and of the of the Bureau of the Evaluation Committee of Inria since 2019.

Islam Boussaada is a member of the Evaluation Committee of the Polish *National Science Centre*, April 2021.

Islam Boussaada is a member of the Scientific Council of Tésa (https://www.tesa.prd.fr) a cooperative research Lab in Telecommunications for Space and Aeronautics in Toulouse, since April 2021.

Islam Boussaada is a member of the Scientific Council of IPSA (https://www.ipsa.fr) Engineering School in Aeronautic and Aerospace since September 2016.

Islam Boussaada is a member of the Development Council of Sup'Biotech (https://www.supbiotech.fr) Engineering School in Biotechnologies since September 2018.

9.1.7 Research administration

Catherine Bonnet is a member of the :

- *Parity Committee* of Inria created since its creation in 2015.
- Bureau du Comité des Projets du CRI Saclay-Ile-de-France since 2018.
- Coordination committee of the Mentoring Program of Inria Saclay-Île-de-France.
- PhD referent committee at L2S, CentraleSupelec.

She is the Parity Referent at L2S for CNRS since its creation in November 2020.

Islam Boussaada is a member of the administration council of the Association SAGIP (https://www.sagip.org), which structures and promotes the disciplines of automatic control and industrial engineering at the national level.

Frederic Mazenc is “Membre de la Commission de Développement Technologique.” (Inria Saclay) since 2019.

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Licence: Islam Boussaada, *Control of bioprocesses*, 27h, 1st year, CentraleSupélec Université Paris-Saclay, France.
- 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: 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.
- 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, *Model representation and analysis*, 15h, 1st year, CentraleSupélec, Université Paris-Saclay.
- Master: Guilherme Mazanti, *Optimization*, 46h, 2nd year, CentraleSupélec, Université Paris-Saclay.
- Doctorat: Silviu Niculescu, *Controlling Delayed Dynamics: Advances in Theory, Methods and Applications*, 7h, CISM Udine, Italy.

9.2.2 Supervision

- PhD in progress: Amina Benarab, Characterization of the exponential decay of linear delay systems solutions, University Paris Saclay. Since 10/2019. Supervisors: Catherine Bonnet, Islam Boussaada and Karim Trabelsi.
- PhD in progress: Naouel Debiane, Bond Graph modeling for robust control and diagnosis of macatronic systems, University of Lille. Since 03/2017. Supervisors: Belkacem Ould-Bouamama and Islam Boussaada.
- PhD in progress: Ali Diab, Commande par filtrage non linéaire des systèmes d'assistance direction, Université Paris-Saclay. Since 10/2019. Supervisors: Giorgio Valmorbida and William Pasillas-Lepine.
- PhD in progress: Ricardo Falcon Prado, Active vibration control of flexible structures under input saturation through delay-based controllers and anti- windup compensators, University Paris Saclay. Since 10/2019. Supervisors: Islam Boussaada and Sami Tliba.
- PhD in progress : Jeanne Redaud, Robust control of a network of linear hyperbolic Partial Differential Equations. Since 11/2020. Supervisors: Jean Auriol and Silviu Niculescu.
- PhD in progress : Amira Remadna, On pole-placement approach for retarded functional differential equations, University Badji Mokhtar-Annaba. Since 09/2019. Supervisors: Islam Boussaada and Azzedine Benchettah.
- PhD in progress: Saeed Sadeghi Arjmand, Mean field games with free final time, École Polytechnique. Since 10/2019. Supervisors: Anne-Sophie de Suzzoni and Guilherme Mazanti.

9.2.3 Juries

- Catherine Bonnet was a member of the Grenoble and Lille Junior Researcher Inria recruiting committees and of the National ARP-SRP Inria recruiting committee. She was a member of the PhD theses of Alejandro Martinez Gonzalez (Université Paris-Saclay), of Souad Amrane (Mouloud Mammeri Univeristy, Tizi Ouzou, Algérie), of Alex Reis de Souza (Université de Lille) and of José de jesus Castillo Zamora (Université Paris-Saclay).
- Islam Boussaada was a reviewer and member of the HDR committee of Cesar Arturo Aceves Lara (INSA Toulouse).
- Islam Boussaada was a reviewer and member of the PhD committee of Berna Bou Farraa (Centrale Nantes).
- Frederic Mazenc was member of the mid-course PhD committee of Salim Zekraoui (supervisors: Wilfrid Perruquetti, Nicolas Espita).
- Giorgio Valmorbida was member of the qualifying PhD committee of Mathieu Bajodek (supervisors: Alexandre Seuret, Frédéric Gouaisbaut).

9.3 Popularization

9.3.1 Education

Catherine Bonnet gave a talk in the dematerialized "Rendez-vous des jeunes mathématiciennes et informaticiennes" https://filles-et-maths.fr/rendez-vous-des-jeunes-mathematiciennes/#presentation, 3 April 2021.

9.3.2 Interventions

Guilherme Mazanti gave a talk at the popular science seminar "Unithé ou café" at Inria Saclay.

10 Scientific production

10.1 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.

[9] M. B. Saldivar, I. Boussaada, H. Mounier and S.-I. Niculescu. *Analysis and Control of Oilwell Drilling Vibrations*. Springer International Publishing, May 2015. URL: https://hal.archives-ouvertes.fr/hal-01123773.

[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.

10.2 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* (2022). URL: https://hal.archives-ouvertes.fr/hal-03530284.

[14] T. Balogh, I. Boussaada, T. Insperger and S.-I. Niculescu. 'Conditions for stabilizability of time-delay systems with real-rooted plant'. In: *International Journal of Robust and Nonlinear Control* (22nd July 2021). DOI: 10.1002/rnc.5698. URL: https://hal.archives-ouvertes.fr/hal-03277678.

[15] A. L. J. Bertolin, R. C. L. F. Oliveira, G. Valmorbida and P. L. D. Peres. 'An LMI Approach for Stability Analysis and Output-Feedback Stabilization of Discrete-Time Lur'e Systems Using Zames-Falb Multipliers'. In: *IEEE Control Systems Letters* 6 (3rd June 2021), pp. 710–715. DOI: 10.1109/LCSYS.2021.3086427. URL: https://hal.archives-ouvertes.fr/hal-03485392.

[16] I. Boussaada, G. Mazanti and S.-I. Niculescu. 'Some Remarks on the Location of Non-Asymptotic Zeros of Whittaker and Kummer Hypergeometric Functions'. In: *Bulletin des Sciences Mathématiques* (17th Dec. 2021). DOI: 10.1016/j.bulsci.2021.103093. URL: https://hal.archives-ouvertes.fr/hal-03250426.

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[18] L. Burlion, V. Gibert, M. Malisoff and F. Mazenc. 'Controls for a Nonlinear System Arising in Vision Based Landing of Airliners'. In: *International Journal of Robust and Nonlinear Control* (2021). URL: https://hal.inria.fr/hal-03483398.

[19] Y.-J. Chen, X.-G. Li, Y. Zhang, S.-I. Niculescu and A. Cela. 'Stability analysis of car-following systems with uniformly distributed delays using frequency-sweeping approach'. In: *IEEE Access* (2021). DOI: 10.1109/ACCESS.2021.3077513. URL: https://hal-centralesupelec.archives-ouvertes.fr/hal-03219166.

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[21] Y. Chitour, G. Mazanti and M. Sigalotti. 'On the gap between deterministic and probabilistic joint spectral radii for discrete-time linear systems'. In: *Linear Algebra and its Applications* 613 (15th Mar. 2021), pp. 24–45. DOI: 10.1016/j.laa.2020.12.013. URL: https://hal.archives-ouvertes.fr/hal-01961003.

[22] R. Griñó, R. Ortega, E. Fridman, J. Zhang and F. Mazenc. 'A Behavioural Dynamic Model for Constant Power Loads in Single-Phase AC Systems'. In: *Automatica* (Sept. 2021). URL: https://hal.inria.fr/hal-03430910.

[23] M. Kuře, J. Bušek, T. Vyhlídal and S.-I. Niculescu. 'Algorithms for cable-suspended payload sway damping by vertical motion of the pivot base'. In: *Mechanical Systems and Signal Processing* 149 (Feb. 2021), p. 107131. DOI: 10.1016/j.ymssp.2020.107131. URL: https://hal-centralesupelec.archives-ouvertes.fr/hal-03108536.

[24] D. Ma, I. Boussaada, J. Chen, C. Bonnet, S.-I. Niculescu and J. Chen. 'PID Control Design for First-Order Delay Systems via MID Pole Placement: Performance vs. Robustness'. In: *Automatica* (31st Dec. 2021). DOI: 10.1016/j.automatica.2021.110102. URL: https://hal.archives-ouvertes.fr/hal-03427550.

[25] G. Mazanti, I. Boussaada and S.-I. Niculescu. 'Multiplicity-induced-dominancy for delay-differential equations of retarded type'. In: *Journal of Differential Equations* 286.15 (18th Mar. 2021), pp. 84–118. DOI: 10.1016/j.jde.2021.03.003. URL: https://hal.archives-ouvertes.fr/hal-02479909.

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[36] X. Yang, B. Zhou, F. Mazenc and J. Lam. 'Global Stabilization of Discrete-Time Linear Systems Subject to Input Saturation and Time Delay'. In: *IEEE Transactions on Automatic Control* (2021). DOI: 10.1109/tac.2020.2989791. URL: https://hal.inria.fr/hal-02565245.

International peer-reviewed conferences

[37] M. A. Abooshahab, M. Hovd and G. Valmorbida. 'Optimal Sensor Placement for Partially Known Power System Dynamic Estimation'. In: IEEE PES ISGT Europe 2021. Espoo, Finland, 18th Oct. 2021. URL: https://hal.archives-ouvertes.fr/hal-03488243.

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[39] J. Auriol, I. Boussaada, H. Mounier and S.-I. Niculescu. 'Torsional-vibrations Damping in Drilling Systems: Multiplicity-Induced-Dominancy based design'. In: MTNS 2021 -24th International Symposium on Mathematical Theory of Networks and Systems. Proceedings of the 24th International Symposium on Mathematical Theory of Networks and Systems. Cambridge, United Kingdom, 2021. URL: https://hal.archives-ouvertes.fr/hal-02893005.

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