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Activity Report 2019

Project-Team DISCO

Dynamical Interconnected Systems in COmplex Environments

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

RESEARCH CENTER
Saclay - Île-de-France

THEME
Optimization and control of dynamic systems

Table of contents

Project-Team DISCO

Creation of the Team: 2010 January 01, updated into Project-Team: 2012 January 01

Keywords:

Computer Science and Digital Science:

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:

B2.2.3. - Cancer
B2.3. - Epidemiology
B2.5. - Handicap and personal assistances
B3.6. - Ecology
B4.3.1. - Biofuels
B5.2.3. - Aviation
B7.2.1. - Smart vehicles

1. Team, Visitors, External Collaborators

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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) [1], [2], [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. [57]). 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 [1], [2].

  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 [10].

  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 [9].

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 [2], [60].

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], [8].

- 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. A recent subject is the modelling of epidemics for tropical diseases.

4.2. Energy Management

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

5. New Results

5.1. Multiplicity-induced-dominancy

Participants: Islam Boussaada, Guilherme Mazanti, Hugues Mounier [L2S, CentraleSupélec], Silviu-Iulian Niculescu.

The effects of multiplicity of spectral values on the exponential stability of reduced-order retarded differential equation were emphasized in recent works. In [13] the general class of second-order retarded differential equations is studied. A parametric multiplicity-induced-dominancy (MID) property is characterized, allowing a delayed stabilizing design with reduced complexity. The proposed approach 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, then, the dominancy is shown using the argument principle.

The work [52] considers retarded differential equations of arbitrary order with a single delay. The existence of a real root with maximal multiplicity is characterized in terms of the equation parameters. This root is shown to be always strictly dominant, determining thus the asymptotic behavior of the system. The dominancy proof is based on improved a priori bounds on the imaginary part of roots on the complex right half-plane and a suitable factorization of the characteristic function, which is an alternative technique to the argument principle.

In [53] we extend the MID property to a given pair of complex conjugate roots for a generic second-order retarded differential equation. Necessary and sufficient conditions for the existence of such a pair are provided, and it is also shown that such a pair is always necessarily dominant. It appears also that when the frequency corresponding to this pair of roots tends to 0, then the pair of roots collapse into a real root of maximal multiplicity. The latter property is exploited in the dominancy proof together with a study of crossing imaginary roots.

In [41] a control-oriented model of torsional vibrations occurring in rotary drilling process is proposed. More precisely, a wave equations with weak damping term is considered. An appropriate stabilizing controller with a reduced number of parameters is proposed for damping such torsional vibrations. Such a controller allows to further explore the effect of multiple roots with maximal admissible multiplicity for linear neutral system with a single delay.

5.2. Pole placement techniques for time-delay systems

Participants: Islam Boussaada, Silviu-Iulian Niculescu, Sami Tliba [L2S, CentraleSupélec], Fazia Bedouhene [University Mouloud Mammeri de Tizi Ouzou, Algeria].

The interest in investigating multiple roots does not rely on the multiplicity itself, but rather on its connection with the dominance of this root, and the corresponding applications in stability analysis and control design. The work [31] extends the analytical characterization of the spectral abscissa for retarded time-delay system with real spectral values which are not necessarily multiple. The effect of the coexistence of such non oscillatory modes on the asymptotic stability of the trivial solution is explored. In particular, the coexistence of an appropriate number of real spectral values makes them rightmost-roots of the corresponding quasipolynomial. Furthermore, if they are negative, this guarantees the asymptotic stability of the trivial solution. As an application of the proposed rightmost-characteristic root assignment, the problem of the vibration damping for a thin flexible beam is considered in [33]. The considered beam is equipped with two piezoelectric patches: one of them works as a sensor and the other as an actuator. Each one of them is bonded on one side of the beam and both are collocated. The model of this system is obtained numerically thanks to a finite element modeling, leading to a linear state-space model. The design of a controller based on proportional and delayed-proportional actions on the input and output signals is proposed, where the properties of the proposed output feedback controller in terms of vibration damping and of robustness is discussed.

5.3. PID tuning for controlling delayed dynamics

Participants: Jie Chen [City University of Hong Kong], Jianqi Chen [City University of Hong Kong], Andong Liu [City University of Hong Kong], Dan Ma [Northeastern University, China], Silviu Niculescu.

Nowadays, the PID controller is the most used in controlling industrial processes. In [21] such a controller is further explored in the control of delayed dynamics. An explicit lower bound on the delay margin of second-order unstable delay systems achievable by PID control is established, which provides a priori a guaranteed range of delay values over which a second-order delay plant can be stabilized by a PID, and more generally, a finite-dimensional LTI controller. This is done by deriving lower bounds on the delay margin achievable by PD controllers, whereas this margin constitutes a lower bound on that achievable by PID controllers. Analysis shows that in most cases our results can be significantly less conservative than the lower bounds obtained elsewhere using more sophisticated, general LTI controllers.

5.4. Frequency-sweeping techniques in delayed dynamics analysis

Participants: Arben Cela [ESIEE Paris], Xu-Guang Li [Northeastern University, China], Xu Li [Northeastern University, China], Jiang-Chian Li [Northeastern University, China], Zhi-Zhong Mao [Shenyang University], Silviu Niculescu, Lu Zhang [Shenyang University].

The stability of linear systems with multiple (incommensurate) delays is investigated in [20], by extending a recently proposed frequency-sweeping approach. First, we consider the case where only one delay parameter is free while the others are fixed. The complete stability w.r.t. the free delay parameter can be systematically investigated by proving an appropriate invariance property. Next, we propose an iterative frequency-sweeping approach to study the stability under any given multiple delays. Moreover, we may effectively analyze the asymptotic behavior of the critical imaginary roots (if any) w.r.t. each delay parameter, which provides a possibility for stabilizing the system through adjusting the delay parameters. The approach is simple (graphical test) and can be applied systematically to the stability analysis of linear systems including multiple delays. A deeper discussion on its implementation is also proposed. Finally, various numerical examples complete the presentation.

In most of the numerical examples of time-delay systems proposed in the literature, the number of unstable characteristic roots remains positive before and after a multiple critical imaginary root (CIR) appears (as the delay, seen as a parameter, increases). This fact may lead to some misunderstandings: (i) A multiple CIR may at most affect the instability degree; (ii) It cannot cause any stability reversals (stability transitions from instability to stability). As far as we know, whether the appearance of a multiple CIR can induce stability is still unclear (in fact, when a CIR generates a stability reversal has not been specifically investigated). In [19], we provide a finer analysis of stability reversals and some new insights into the classification: the link between the multiplicity of a CIR and the asymptotic behavior with the stabilizing effect. Based on these results, we present an example illustrating that a multiple CIR's asymptotic behavior is able to cause a stability reversal. To the best of the authors' knowledge, such an example is a novelty in the literature on time-delay systems.

The work [30] focuses on the stability property of a class of distributed delay systems with constant coefficients. More precisely, we will discuss deeper the stability analysis with respect to the delay parameter. Our approach will allow to give new insights in solving the so-called complete stability problem. There are three technical issues need to be studied: First, the detection of the critical zero roots; second, the analysis of the asymptotic behavior of such critical zero roots; third, the asymptotic behavior analysis of the critical imaginary roots with respect to the infinitely many critical delays. We extended our recently-established frequency-sweeping approach, with which these technical issues can be effectively solved. More precisely, the main contributions of this paper are as follows: (i) Proposing a method for the detection of the critical zero roots. (ii) Proposing an approach for the asymptotic behavior analysis of such critical zero roots. (iii) The invariance property for the critical imaginary roots can be proved. Based on these results, a procedure was proposed, with which the complete stability analysis of such systems was accomplished systematically. Moreover, the procedure represents a unified approach: Most of the steps required by the complete stability problem may be fulfilled through observing the frequency-sweeping curves. Finally, some examples illustrate the effectiveness and advantages of the approach.

5.5. Weierstrass approach to asymptotic behavior of retarded differential equations

Participants: Jie Chen [City University of Hong Kong], Liliana Felix [University of San Luis Potosi], Alejandro Martinez-Gonzalez, Cesar F. Mendez-Barrios [University of San Luis Potosi], Silviu Niculescu.

The work [22] focuses on the analysis of the behavior of characteristic roots of time-delay systems, when the delay is subject to small parameter variations. The analysis is performed by means of the Weierstrass polynomial. More specifically, such a polynomial is employed to study the stability behavior of the characteristic roots with respect to small variations on the delay parameter. Analytic and splitting properties of the Puiseux series expansions of critical roots are characterized by allowing a full description of the cases that can be encountered. Several numerical examples encountered in the control literature are considered to illustrate the effectiveness of the proposed approach.

5.6. Some remarks on the Walton and Marshall method for neutral delay systems

Participants: Catherine Bonnet, Islam Boussaada, Le Ha Vy Nguyen.

The Walton and Marshall method allows to determine stability windows of delay systems of the retarded and neutral type. We noticed that some delay systems of the neutral type do not behave as claimed in [59] and analyzed carefully the position of the poles of such systems in the right half-plane. We have considered delay systems with characteristic equation being a quasi-polynomial with one delay and polynomials of degree one. It is shown that for a subclass of systems which have a chain of poles clustering the imaginary axis by the left, the procedure of Walton and Marshall fails: we prove the existence, for an infinitesimally small delay, of a positive real pole at infinity. This real pole is then proved to be the unique pole of the system in the closed right half-plane for all values of the delay. Some numerical examples illustrate the results [39]. We are currenlty extending those results to the general case of polynomials of degree $n > 1$.

5.7. $L2$ and BIBO Stability of systems with variable delays

Participants: Catherine Bonnet, Jonathan R. Partington [Univ of Leeds,U.K.].

There has been a growing interest in systems with time-varying delays in recent years and to the best of our knowledge, no study has been made of the input–output stability of a standard feedback scheme involving a system with time-varying delays. We have considered two versions of input–output stability: so-called Hinfinity and BIBO-stability. Retarded and neutral type systems with pointwise or distributed delays are studied here. We perform a stability analysis and discuss feedback stabilization. The results we derive yield very explicit estimates for stability margins [40].

5.8. Stability Analysis of Linear Partial Differential Equations

Participants: Giorgio Valmorbida, Aditya Gahlawat [University of Illinois at Urbana-Champaign].

We proposed a method to perform stability analysis of one-dimensional Partial Integro-Differential Equations. The relevance of the proposed results lies on the fact that we cast the Lyapunov inequalities as a differential inequality in two dimensions. The proposed structure for the inequalities is motivated by the same structure as the one used in the study of backstepping feedback laws, a successful strategy applied for several one-dimensional PDE systems. The advantage of the proposed Lyapunov analysis can be studied in a simpler manner as well as the fact that the backstepping law can be approximated by simpler laws and the stability can still be studied trhough the solution to the set of proposed inequalities.

We rely on Lyapunov analysis to establish the exponential stability of the systems. Then we present a test for the verification of the underlying Lyapunov inequalities, which relies on the existence of solutions of a system of coupled differential equations.

We illustrate the application of this method in several examples of PDEs defined by polynomial data, we formulate a numerical methodology in the form of a convex optimization problem which can be solved algorithmically. We show the effectiveness of the proposed numerical methodology using examples of different types of PDEs.

We are currently studying the extensions of coupled PDE-ODE systems.

5.9. 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].

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. 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.

The obtained formulation opens several possibilities to study the class of piecewise affine systems and their robustness properties. Indeed the fact that some partitions are uncertain is more easily coped with the proposed approach as they are described as parametric uncertainties of the implicit representation. Also, systems of larger dimension can be studied.

The stability analysis of the particular subclass of systems given by asymmetric saturation can also be performed with discontinuous Lyapunov functions for discrete-time systems.

5.10. Set Invariance for Descriptor Systems

Participants: Giorgio Valmorbida, Ye Wang [Universidade Federal do Rio Grande do Sul], Sorin Olaru [L2S, CentraleSupélec], Vicenç Puig [Universitat Politècnica de Catalunya], Gabriela Cembrano [Universitat Politècnica de Catalunya].

Some descriptor systems, characterized by a difference-algebraic relation, appear in economic systems. For such a class of systems we study robust invariant set characterizations of discrete-time descriptor systems and propose an active mode detection mechanism. The considered class of descriptor systems assumes regularity, stability and is affected by unknown-but-bounded disturbances.

As a first theoretical result, we establish a general framework for robust invariant sets for discrete-time descriptor systems in both causal and non-causal cases. Particular transformations are subsequently proposed for handling causal and non-causal descriptor systems and will be used to characterize the effects of disturbances. Based on these set-theoretic notions and a designed input signal for active set separations, we propose an active mode detection mechanism by exploiting the strong invariance properties.

5.11. New advances on backstepping

Participants: Frédéric Mazenc, Michael Malisoff [LSU], Laurent Burlion [Rutgers Univ.].

We worked on the problem of improving a major control design technique for nonlinear continuous-time systems called backstepping by using a fundamentally new approach which uses as key ingredient the introduction in the control of artificial delays or the use of dynamic extensions.

In the paper [24], we adopted a technique which is based on the introduction of pointwise delays (and not of distributed terms) to solve a challenging input-to-state stabilization problem for a chain of saturated integrators when the variables are not accurately measured. Let us observe that classical backstepping does not apply in the considered case.

In the paper [23], we constructed bounded globally asymptotically stabilizing output feedbacks for a family of nonlinear systems, using a dynamic extension and a converging-input-converging-state assumption. We provided sufficient conditions for this assumption to hold, in terms of Lyapunov functions. The novelty is that our construction provides formulas for the control bounds while allowing uncertainties that prevent the use of classical backstepping in cases where only part of the state variable is available. We illustrated our work with an engineering application: the single-link direct-drive manipulator.

5.12. Finite time observers

Participants: Frédéric Mazenc, Michael Malisoff [LSU], Saeed Ahmed [University of Kaiserslautern, Germany], Thach Dinh [CNAM], Tarek Raissi [CNAM].

Finite time observers are remarkably efficient when the value of the state is needed in a short time. By contrast with them, the solutions asymptotic observers may take a long time to be close to the solutions of the studied systems and may exhibit large transient errors. Motivated by this general fact, we produced three works.

In the work [12], we proposed finite time observers for time-varying nonlinear systems with delays in the outputs. When disturbances are present, we provide approximate values for the solutions which are expressed as upper bounds on the approximation errors after a suitable finite time. We illustrated our work via systems arising in the study of vibrating membranes, where time-varying coefficients can be used to represent intermittent measurements.

In paper [36], we use finite time reduced order continuous-discrete observers to solve an output feedback stabilization problem for a broad class of nonlinear systems whose output contains uncertainty. Unlike earlier works, our feedback control is discontinuous, but it does not contain any distributed terms, which is an advantage because the implementation of these terms may cause instability. We illustrated our main result by applying it to design a dynamic output feedback to solve a tracking problem for nonholonomic systems in chained form.

The paper [35] is devoted to the construction of finite time observers for discrete-time systems. We developped a new technique, which uses past values of the output. We considered the case where the systems are affected by additive disturbances and disturbances in the output. Exact estimation or approximate estimation have been achieved, depending on the absence or the presence of unknown but bounded uncertainties, respectively.

5.13. Observers with discrete measurements

Participants: Frédéric Mazenc, Michael Malisoff [LSU], Saeed Ahmed [University of Kaiserslautern, Germany].

We studied the important case where the measurements of a system are discrete because output of this type may preclude the use of observers designed under the assumption that the measurements are continuous.

In the paper [25], we have studied time-varying linear systems in the difficult case where the inputs and outputs have sampling and delays, and where the systems and outputs contain uncertainties. The observers we have proposed are of continuous-discrete type and have no distributed terms. We allowed the delays to be arbitrarily large and proved that the observer in combination with a linear control result in an input-to-state stability, under delays and sampling. We illustrated our work in two examples including a DC motor model.

In the work [38], we have revisited a well-known contribution of observer design for continuous-time systems with discrete measurements which relies on a dynamic extension. Using a stability analysis which relies on the recent technique called "trajectory based approach", we proved that, for systems with asynchronous sampling, the proposed dynamic observer is converging even when the size of some (sufficiently scarce) intervals between 2 measurements is larger than the upper bound ensuring convergence of the observer that is provided in the literature. A scarcety condition on these intervals is exhibited.

5.14. Observer for a rigid body

Participants: Frédéric Mazenc, Maruthi Akella [University of Texas, USA], Hongyang Duong [Harbin Institute of Technology], Qinglei Hu [Beihang University].

In the work [15], observers are proposed for models of rigid bodies in the case where only a part of the state variables can be measured. The design is based on the dual-quaternion description. To achieve tracking control objectives, the proposed observer are combined with an independently designed proportional-derivative-like feedback control law (using full-state feedback), and a special Lyapunov "strictification" process is employed to ensure a separation property between the observer and the controller. Almost global asymptotic stability of the closed-loop dynamics is guaranteed. We performed numerical simulations for a prototypical spacecraft pose tracking mission application to illustrate the effectiveness and robustness of the proposed method.

5.15. Systems with pointwise delays

Participants: Frédéric Mazenc, Michael Malisoff [LSU], Robledo Gonzalo [Univ. de Chile, Chile], Silviu Niculescu.

Frequently, the presence of delays is an obstacle to the stability analysis or the control of systems. Two of our works originate in the will to overcome this obstacle, in two distinct contexts.

The contribution [26] is devoted to the study of a model of a chain of two bio-reactors called 'chemostats'. One contains two microbial species in competition for a single limiting nutrient and receives an external input of the less advantaged competitor, which is cultivated in the other one. Pointwise delays are present. Under a condition on their size, we obtained sufficient conditions ensuring coexistence of all the species in competition. To prove the result, we adopted a Lyapunov based technique.

The contribution of [37] is twofold. In a first part, we exhibited a fundamental feature of the systems with a pointwise periodic time-varying delay: we have shown by a counterexample that the asymptotic stability of such a system cannot be deduced from the average value of the delay (even when the delay is 'rapidly' varying). In a second part, motivated by this counterexample, we proposed a new representation of systems with time-varying delays, which is helpful to carry out stability analyses and to develop a new state feedback stabilization method.

5.16. Control of an aircraft

Participants: Frédéric Mazenc, Michael Malisoff [LSU], Laurent Burlion [Rutgers Univ.].

The work [34] adapts some ideas we published in previous contributions to a control problem for a chain of saturating integrators for dynamics with outputs that occurs in the vision based landing of aircraft. The major obstacle that we overcome is due to the fact that only imprecise output measurements are available. The control laws we designed are bounded by an arbitrarily small constant. The closed-loop systems we obtained possess the robustness property called "local input-to-state stability".

5.17. Effect of environment on population dynamics

Participants: Islam Boussaada, Silviu Niculescu, Jun-Xiu Chen [Nothestern University], Sette Diop [L2S, CentraleSupélec], Xu-Guang Li [Nothestern University], Paul Raynaud de Fitte [LMRS, Université de Rouen Normandie], Safia Slimani [LMRS, Université de Rouen Normandie], Sami Tliba [L2S, CentraleSupélec].

Competition in population dynamics is often considered to be governed by predator-prey models. In particular, Lotka-Volterra models are intensively used in this context.

A modified version of a prey-predator system with Leslie-Gower and Holling type II functional responses incorporating a refuge for preys is studied in [27]. Such a refuge substantially complicates the dynamics of the system. We study the local and global dynamics and the existence of limit-cycles. We also investigate conditions for extinction or existence of a stationary distribution, in the case of a stochastic perturbation of the system.

Most of the reported Lotka-Volterra examples have at most one stability interval for the delay parameters. Furthermore, the existing methods fall short in treating more general case studies. Inspired by some recent results for analyzing the stability of time-delay systems, this paper focuses on a deeper characterization of the stability of Lotka-Volterra systems w.r.t. the delay parameters. In [58], we introduced the recently-proposed frequency-sweeping approach to study the complete stability problem for a broad class of linearized Lotka-Volterra systems. As a result, the whole stability delay-set is analytically determined. Moreover, as a significant byproduct of the proposed approach, some Lotka-Volterra examples are found to have multiple stability delay-intervals. In some situations, a longer maturation period of species is helpful for the stability of a population system.

In another context, the effect of environment on yeast population dynamics is studied in [28]. In presence of oxygen cells usually adopt efficient metabolism in order to maximize energy production yield in poor diet. If nutrient resource increases, a metabolic shift from efficient metabolism (respiration) to inefficient metabolism (fermentation) is reflecting a minimal cost principle of living systems to optimize fitness. This is known as the Crabtree/Warburg effect. A model that describes the population dynamics of cells and the input growth condition is established. Proof of principle has been constructed using a battery of growth experiments on Crabtree-positive yeasts–Saccharomyces under various conditions of glucose in aerobic and micro-aerobic conditions. General cell growth model estimating metabolic shift has been constructed based on an Auto-Regressive approach.

5.18. Distributed Algorithms for Microbiological systems

Participants: Lotfi Baour, Catherine Bonnet, Da-Jung Cho, Walid Djema [BIOCORE project team], Lucas Leclerc, Matthias Fuegger [MEXICO project team], Frédéric Mazenc, Tomas Nowak [LRI, Univ Paris-Sud], Cristina Stoica [CentraleSupélec].

This project led by M. Fuegger and T. Nowak considers microbiological distributed systems such as bacterial cultures. Our goal is to develop algorithms to be used in such low-powered biological computing systems. We have considered a distributed computation model where bacteria communicate via concentrations of small signaling molecules. Algorithms designed for such a model are of importance to provide services like clock synchronization. Basic ODE models for well-mixed solutions are readily available from systems biology. This year, we have paid attention to ODE and PDE models presented in [56], [55]. We have analyzed the influence of model parameters on the stability of the system. Moreover, looking at the involved basic biochemical reactions we have considered some changes in the modelling.

6. Partnerships and Cooperations

6.1. Regional Initiatives

Islam Boussaada is a deputy director of the IRS iCODE Institute, the institute for control and decision of the Idex Paris Saclay (http://icode-institute.fr).

- The project *Distributed Algorithms for Microbiological Systems* was funded by iCODE.
- The project *Symbolic/Numerical Methods and Implementations in Delayed-Control design* was funded by iCODE.
- The project *From modeling to control of microalgae growth in photo-bioreactor* was funded by iCODE.
- The project *Distributed Algorithms for Microbiological systems* was funded by iCODE.

6.2. National Initiatives

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.

6.2.1. ANR

Giorgio Valmorbida is a member of the ANR HANDY - Hybrid And Networked Dynamical sYstems (http://projects.laas.fr/handy). Project Summary: Networked dynamical systems are ubiquitous in current and emerging technologies. From energy grids, fleets of connected autonomous vehicles to online social networks, the same scenario arises in each case: dynamical units interact locally to achieve a global behavior. When considering a networked system as a whole, very often continuous-time dynamics are affected by instantaneous changes, called jumps, leading to so-called hybrid dynamical systems. The jumps may originate from (i) the intrinsic dynamics of the nodes, like in multimedia delivery with fixed rate encoding, (ii) intrinsic limitations of the control actions, possibly constrained to a finite set of possible selections, like in power converters within energy grids, (iii) the creation/loss of links or the addition/removal of nodes like in renewable energy systems and social networks. Hybrid phenomena thus play an essential role in these control applications, and call upon the development of novel adapted tools for stability and performance analysis and control design. In this context, the aim of HANDY project is to provide methodological control-oriented tools for realistic networked models, which account for hybrid phenomena.

6.3. European Initiatives

6.3.1. Collaborations in European Programs, Except FP7 & H2020

Program: **COST Action**

Project acronym: FRACTAL

Project title: Fractional-order systems; analysis, synthesis and their importance for future design

Duration: November 2016 - October 2020

Coordinator: Jaroslav Koton Czech Republic

Abstract: Fractional-order systems have lately been attracting significant attention and gaining more acceptance as generalization to classical integer-order systems. Mathematical basics of fractional-order calculus were laid nearly 300 years ago and since that it has gained deeply rooted mathematical concepts. Today, it is known that many real dynamic systems cannot be described by a system of simple differential equation or of integer-order system. In practice we can encounter such systems in electronics, signal processing, thermodynamics, biology, medicine, control theory, etc. The Action will favor scientific advancement in above mentioned areas by coordinating activities of academic research groups towards an efficient deployment of fractal theory to industry applications.

Program: **PHC AURORA**

Project acronym: -

Project title: Control and Observation of Nonlinear Systems

Duration: 01/2019-12/2019

Coordinator: Giorgio VALMORBIDA

Other partners: NTNU, Norvège

Abstract: Control theory and controller design for linear dynamical systems is well developed. The same cannot be said for nonlinear systems and searching for a general set of design tools applicable to any nonlinear system may be futile. Restricting the class of system dynamics with the aim of developing a more complete set of controller design tools for such a restricted model class therefore appears to be a reasonable approach. One such restricted class of system dynamics is the class of polynomial dynamical systems, for which stability analysis and controller design tools based on Convex Optimization has recently flourished, using so-called Sum of Squares (SOS) programming. Three topics were studied: - Time discretization techniques. SOS programming for discrete time system is less developed than for continuous time systems. This research task will then study discretization techniques leading to polynomial or rational models. In particular we will develop methods to compare the continuous time system and the discretized one by, for instance, comparing estimates of the region of attraction of stable equilibria. - Observer design. In many applications, not all states are measured, and therefore they have to be inferred using a state observer. Note that the so-called Certainty Equivalence Principle does not in general hold for nonlinear systems. This research task will therefore address observer design using SOS programming, and study the effects of interactions between controller design and observer design on the stability of the overall system. - Benchmark application. CentraleSupelec has a cart and pendulum experimental setup. The complexity of SOS-based controller design for this system is near the limit of what can be accommodated by current optimization packages and computational resources. This research task will test the limits of available numerical solution tools and provide a convincing demonstration of the capabilities of SOS-based controller design.

Program: **PHC BALATON**

Project acronym: SadHuB

Project title: Analysis of stabilizability of delayed dynamical system as function of the systems parameters and the time delays with applications to human balancing

Duration: 01/2018-12/2019

Coordinator: Islam Boussaada

Other partners: Budapest University of Technology and Economics, Hungary

Abstract: Motivated by a class of Time-delay systems occurring in modeling of many mechanical engineering applications, this project aims to associate researchers from control theory, applied mathematics and mechanical engineering to build together a general methodology for the analysis and control of mechanical/bio-mechanical structures. In particular, the human balance is often considered as a control system which operates 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. A particular interest will be devoted to the delayed human balance, where a depthful study of the delay effect on the stability is expected.

6.4. International Initiatives

6.4.1. Inria International Partners

6.4.1.1. Informal International Partners

- Louisiana State University, Baton Rouge, USA
- Rutgers University, USA
- CINVESTAV, IPN, Mexico-City, Mexico
- Southern Illinois University, USA
- The University of Texas at Austin, Dept. of Aerospace Engineering & Engineering Mechanics, USA
- City University of Hong Kong, China
- Czech technical university in Prague, Czech Republic
- Budapest University of Technology and Economics, Hungary
- Katholieke Universiteit Leuven, Belgium
- Blikent University, Turkey
- Northeastern University, China
- Northeastern University, Boston, USA
- Universidad de Chile, Chile
- School of Mathematics, University of Leeds, U.K.
- UNICAMP, Brazil

- Kyoto University, Japan
- University Badji Mokhtar-Annaba, Algeria
- University Mouloud-Mammeri Tizi Ouzou, Algeria
- Universitat Politècnica de Catalunya, Spain
- University of Melbourne, Australia

6.4.2. Participation in Other International Programs

The team is member of the GDRI (International Research Group funded by CNRS) SpaDisco (following the GDRI Delsys) since 2017.

6.5. International Research Visitors

6.5.1. Visits of International Scientists

Jie Chen, CityU Hong Kong, 16-20 Dec 2019.

André Fioravanti, UNICAMP, Brazil, 1-7 Dec 2019.

Dan Ma, Northeastern University, 16-20 Dec 2019.

Hitay Özbay, Bilkent University, 4-8 Dec 2019.

Matheus Souza, UNICAMP, Brazil, 1-7 Dec 2019.

Joao Manoel Gomes da Silva Jr, UFRGS, Brazil, 15 Jul -15 Ago 2019.

Ross Drummond, University of Oxford, U.K., 1-7 Dec 2019.

Yutaka Yamamoto, Kyoto University, Japan, 30 oct - 8 Dec 2019.

6.5.1.1. Internships

Master internship: Lotfi Baour, Qualitative behaviour of two models of bacteria communication, Université de Cergy-Pontoise. Supervisors: Catherine Bonnet, Walid Djema, Matthias Fuegger and Thomas Nowak.

Master internship: Khaoula El Farhani, Modeling, estimation and control of microalgae growth for energy production and synthesis of molecules of high added values, CentraleSupelec, 05-09/2019. Supervisors: Sette Diop and Islam Boussaada.

Master internship: Jawher Kahouli, estimation and modelling of microalgae growth in photobioreactor, IPSA/Sup'Biotech,02-08/2019. Supervisors: Islam Boussaada, Ali El Ati and Jean-Yves Trosset.

Master internship: Robin Lacombe, qualification and start-up of Synoxis nano 2l photobioreactor, IPSA/Sup'Biotech,02-08/2019. Supervisors: Islam Boussaada, Ali El Ati and Jean-Yves Trosset.

Master internship: Lucas Leclerc, Modelling of bacteria communication through EDO/EDP, CentraleSupélec. Supervisor: Catherine Bonnet, Matthias Fuegger and Thomas Nowak.

Master internship: Javier Eduardo Pereyra Zamundio, New backstepping design using satificial delays for systems with pointwise delays, CINVESTAV, Instituto Politecnico Nacional. Supervisors: Sabine Mondié, Frédéric Mazenc.

6.5.2. Visits to International Teams

Islam Boussaada visited Budapest University of Technology and Economics during 1-7 Dec 2019.

Giorgio Valmorbida visited the University of Oxford 15-17 Jul 2019.

Giorgio Valmorbida visited the UFRGS, CEFET-Divinopolis, and the UNICAMP, Brazil 26 Jul - 6 Ago 2019.

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events: Organisation

7.1.1.1. General Chair, Scientific Chair

Islam Boussaada is co-leading the national research group *Tools for analysis and synthesis of infinite-dimensional systems* (GT OSYDI) of the CNRS/GDR MACS (https://gdr-macs.cnrs.fr/groupe-de-travail/osydi).

7.1.1.2. Member of the Organizing Committees

Catherine Bonnet was member of the organizing committee of SIAM CT19, Chendu China, July 2019.

7.1.2. Scientific Events: Selection

- Catherine Bonnet was Associate Editor for the 2019 American Control Conference, Philadelphia, USA and the 2020 American Control Conference, Denver, USA.
- Catherine Bonnet and Islam Boussaada were Associate Editor for the Joint IFAC Conference 7th Symposium on System Structure and Control (SSSC 2019) and 15th IFAC Workshop on Delay Systems, Sinaia, Roumania, Sept 2019.
- Frédéric Mazenc was Associate Editor for the conferences 2019 American Control Conference, Philadelphia, USA and for the European Control Conference 2020, St Petersburg.
- Giorgio Valmorbida was an Associate Editor for the 2019 American Control Conference, Philadelphia, USA and the 2020 American Control Conference, Denver, USA. He was also Associate editor for the 58th Conference in Decision and Control, Nice, France. Silviu Niculescu is the IEEE CSS (Control System Society) representative for the series of IEEE Conferences (nternational Conference on System Theory, Control and Computing,): http://icstcc2019.cs.upt.ro

7.1.2.1. Member of the Conference Program Committees

- Catherine Bonnet and Giorgio Valmorbida are members of the scientific committee of the GDRI (International Research Group funded by CNRS) SpaDisco since 2017.
- Giorgio Valmorbida is a member of the steering committee of the GDRI (International Research Group funded by CNRS) SpaDisco since 2017.
- Catherine Bonnet and Islam Boussaada were members of the International Program Committee of the Joint IFAC Conference 7th Symposium on System Structure and Control (SSSC 2019) and 15th IFAC Workshop on Delay Systems, Sinaia, Roumania, Sept 2019.

7.1.2.2. Reviewer

The team reviewed papers for several international conferences including IEEE Conference on Decision and Control, IEEE American Control Conference, European Control Conference ...

7.1.3. Journal

7.1.3.1. Member of the Editorial Boards

Frédéric Mazenc is member of the editorial boards of the following journals:

- Asian Journal of Control : Editor;
- IEEE Transactions on Automatic Control, Associate Editor;
- European Journal of Control, Associate Editor;
- Journal of Control and Decision, Associate Editor;
- IEEE Control Systems Letters, Associate Editor.

Silviu Niculescu is the Founding Editor and the Editor-in-Chief (since its creation in 2012) of the Springer (hard-cover) book series Advances in Delays and Dynamics ADD@S https://www.springer.com/series/11914.

He is Associate Editor at European Journal of Control (since 2011).

7.1.3.2. 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 ...

7.1.4. Invited Talks

Giorgio Valmorbida was invited to give a talk in the workshop Scientific Computing Across Scales: Extreme Events and Criticality in Fluid Mechanics in April 15 - 18, 2019, at The Fields Institute 15-17, Toronto, CA.

Frédéric Mazenc was invited to give a talk in the CINVESTAV, IPN: Model Reduction and Predictor Control, in August 2, 2019, Mexico City, Mexico.

7.1.5. Leadership within the Scientific Community

Catherine Bonnet is a member of the IFAC Technical Committees on *Distributed Parameter Systems* and on *Biological and Medical Systems*. She is a member of the management committee of the COST Action FRACTAL (2016-2020).

Silviu Niculescu is the chair of the IFAC TC 2.2 "Linear Control Systems" since 2017 (including 300-350 researchers throught the world). The TC is coordinating 4 "Working Groups" (WG) including the WG on "Time-Delay Systems".

7.1.6. Scientific Expertise

Since September 2015, Catherine Bonnet is a member of the Evaluation Committee of Inria and since 2019 of the Bureau of the Evaluation Committee of Inria.

Since September 2016, Islam Boussaada is a member of the Scientific Council of IPSA (Engineering School in Aeronautic and Aerospace approved by CTI).

Since September 2018, Islam Boussaada is a member of the Development Council of Sup'Biotech (Engineering School in Biotechnologies approved by CTI).

Since 2014, Frédéric Mazenc is an expert for the FNRS (Belgium). His mission consists in evaluating research projects funded by this institution.

Since 2012, Frédéric Mazenc is a, expert for the ANVUR (National Agency for the Evaluation of Universities and Research Institutes, Italy). His mission consists in evaluating the contribution of Italian scientists.

Since 2011, Frédéric Mazenc is a, expert for the Romanian National Council for Development and Innovation (Romania). His mission consists in evaluating research projects funded by the this institution.

7.1.7. Research Administration

Catherine Bonnet is a member of the

- *Parity Committee* of Inria created sice 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.
- Administration council of the association *Femmes et Mathématiques*

Since October 2017, Frédéric Mazenc is Correspondant Inria Saclay A.M.I.E.S., http://www.agence-maths-entreprises.fr/. Since September 2019, he is member of "la Commission de Déloppement Technologique". He is member of the “Conseil du Laboratory of Signal and Systems".

7.2. Teaching - Supervision - Juries

7.2.1. 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, *Tutorials - Modelling, Control, Optimization and Electrical Machines*, 1st and 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 : Catherine Bonnet, *Stability properties and stabilization of interconnected dynamical systems involving delays*, 20h, IPSA, France.

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.

Doctorat : Silviu Niculescu, *Controlling Delayed Dynamics: Advances in Theory, Methods and Applications*, 7h, CISM Udine, Italy.

7.2.2. Supervision

PhD in progress: Souad Amrane, on real pole-placement for retarded functional differential equations, University Mouloud Mammeri. Since 09/2017. Supervisors: Fazia Bedouhene and Islam Boussaada.

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: Caetano Cardeliquio, Contributions to the Theory of Time-Delay Systems: Stability and Stabilisation, UNICAMP & Université Paris Saclay, 27 September 2019; Supervisors : Catherine Bonnet and André Fioravanti.

PhD in progress: Leonardo Broering Groff, Commande Périodique Déclenché par Événements, Université Paris-Saclay et UFRGS. Since 03/2017. Supervisors: Giorgio Valmorbida and Joao Manoel Gomes da Silva Jr.

PhD in progress: Jose Castillo, Design, Modeling and control of multi drones for aerial handling, University Paris Saclay, 10/2018, Islam Boussaada and Juan Escareno.

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: Javier Eduardo Pereyra Zamundio, New backstepping design for systems with delay: finite time stabilization, robust stabilization, CINVESTAV, Instituto Politecnico Nacional. Since 10/2019. Supervisors: Sabine Mondié and Frédéric Mazenc.

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.

Postdoc: Da-Jung Cho, Modelling of bacteria communication, May-August 2019. Supervisors: Catherine Bonnet, Matthias Fuegger and Thomas Nowak.

7.2.3. Juries

- Catherine Bonnet was member of the Grenoble and Nancy Junior Researcher Inria recruiting committees.
- Catherine Bonnet was President of the PhD thesis of Yanqiao Wei *'Non-asymptotic and Robust fractional order differentiators using generalized modulating functions'*, 15 November 2019, INSA Val de Loire.

7.3. Popularization

7.3.1. Interventions

- The team welcomed Sophie Merheb, high-school student of Lycée privé Notre-Dame Les Oiseaux, Verneuil-sur-Seine, for the period 17-26 June 2019.

8. Bibliography

Major publications by the team in recent years

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