Activity Report 2018

Team NON-A POST

Non-Asymptotic estimation for online systems

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Lille - Nord Europe

THEME
Optimization and control of dynamic systems

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Team NON-A POST

Creation of the Team: 2018 January 01, end of the Team: 2018 December 31

Keywords:

Computer Science and Digital Science:

A5.1.1. - Engineering of interactive systems
A5.1.5. - Body-based interfaces
A5.9.1. - Sampling, acquisition
A5.9.2. - Estimation, modeling
A5.10.3. - Planning
A5.10.4. - Robot control
A5.10.6. - Swarm robotics
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.4.1. - Deterministic control
A6.4.3. - Observability and Controlability
A6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

B3.4.3. - Pollution
B4.5. - Energy consumption
B5.6. - Robotic systems
B6.4. - Internet of things
B6.6. - Embedded systems
B7.1. - Traffic management
B7.1.2. - Road traffic
B7.2.1. - Smart vehicles

1. Team, Visitors, External Collaborators

Research Scientists

Denis Efimov [Team leader, Inria, Researcher, HDR]
Andrey Polyakov [Inria, Researcher, HDR]

Faculty Member

Jean-Pierre Richard [Permanent head, Centrale Lille, Professor, HDR]

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Tonametl Sanchez Ramirez [ANR]

PhD Students

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Francisco Lopez Ramirez [Inria]
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Haik Jan Silm [EC Lille-KUL]

Jijju Thomas [EC Lille-TU Eindhoven]
Quentin Voortman [TU Eindhoven-EC Lille]
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External Collaborators
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Leonid Fridman [Professor, UNAM, Inria International Chair]

2. Overall Objectives

2.1. Objectives

For engineers, a wide variety of information cannot be directly obtained through measurements. Some parameters (constants of an electrical actuator, delay in a transmission, etc.) or internal variables (robot's posture, torques applied to a robot, localization of a mobile robot, etc.) are unknown or unmeasured. In addition, usually the signals from sensors are distorted and tainted by measurement noises. In order to simulate, to control or to supervise processes, and to extract information conveyed by the signals, one has to estimate parameters or variables.

Estimation techniques are, under various guises, present in many parts of control, signal processing and applied mathematics. Such an important area gave rise to a huge international literature. From a general point of view, the performance of an estimation algorithm can be characterized by three indicators:

- The computation time (the time needed to obtain the estimation). Obviously, the estimation algorithms should have as small as possible computation time in order to provide fast, real-time, on-line estimations for processes with fast dynamics.
- The algorithm complexity (the easiness of design and implementation). Estimation algorithms should have as low as possible algorithm complexity, in order to allow an embedded real-time estimation (for example, in Internet of things, the embedded computation power is limited and can be even more limited for small sensors/actuators devices). Another question about complexity is: can an engineer appropriate and apply the algorithms? For instance, an algorithm application is easier if the parameters have a physical meaning w.r.t. the process under study.
- The robustness. The estimation algorithms should exhibit as much as possible robustness with respect to a large class of measurement noises, parameter uncertainties, discretization steps and other issues of numerical implementation. A complementary point of view on robustness is to manage a compromise between existence of theoretical proofs versus universalism of the algorithm. In the first case, the performance is guaranteed in a particular case (a particular control designed for a particular model). In the second case, an algorithm can be directly applied in "most of the cases", but it may fail in few situations.

Within the very wide area of estimation, *Non-A POST* addresses 3 particular theoretical challenges:

1) Development of theory of dynamical homogeneous systems;

2) Estimate on-line the derivatives of a signal;

3) Design of control and estimation algorithms converging in finite and in fixed time.

All of them are connected with the central idea of designing or exploiting algorithms with the finite-time convergence property. In particular, the *non-asymptotic* estimation techniques (numerical differentiation, finite-time differentiators or observers) constitute a central objective of the project, explaining the name *Non-Asymptotic estimation for on-line systems*. Below, these 3 challenges will be shortly described in relation to the above indicators.

The researches developed by *Non-A POST* are within the continuity of the project-teams *Non-A* and *ALIEN* in what concerns the *algebraic tools* that are developed for finite-time estimation purposes. However, *Non-A POST* also aims at developing complementary estimation techniques, still aiming at the finite-time performance but based on the so-called *higher-order sliding mode* algorithms, interval estimation techniques and, as well as, fixed-time algorithms.

Non-A POST also wants to confront these theoretical challenges with some application fields: Networked robots, Nano/macro machining, quadrotors, active flow control, *etc*. Today, most of our effort (*i.e.*, engineering staff) is devoted to the first item, according to the theme "Internet of Things" (IoT) promoted by Inria in its Strategic Plan for the Lille North-Europe research center.

3. Research Program

3.1. Theory of homogeneous systems

Homogeneity is a property of mathematical objects, such as functions or vector fields, to be scaled in a consistent manner with respect to a scaling operation (called a dilation) applied to their argument (a kind of symmetry). The first rise of homogeneity deals with homogeneous polynomials investigated by L. Euler in 18^{th} century. In 50s and 60s more generic notions of homogeneity (weighted and coordinate-free or geometric) have been introduced by V.I. Zubov and his group. For example, a function $f : \mathbb{R}^n \to \mathbb{R}$ is called homogeneous (in Euler's sense) if

$$f(\lambda x) = \lambda^{1+\nu} f(x) \quad \forall x \in \mathbb{R}^n,\ \forall \lambda > 0$$

for some $\nu \geq -1$ called the degree of homogeneity of f (a parameter of symmetry). Such a type of symmetry leads to the scaling of trajectories of resultant dynamical systems, *e.g.* for

$$\dot{x}(t) = f\left(x(t)\right) \quad t \geq 0,\ x(0) = x_0 \in \mathbb{R}^n$$

denote a solution corresponding to the initial condition x_0 by $X(t, x_0)$, then

$$X(t, \lambda x_0) = \lambda X(\lambda^\nu t, x_0) \quad \forall x_0 \in \mathbb{R}^n,\ \forall \lambda > 0.$$

So homogeneous systems possess several important and useful properties: their local behavior is the same as global one, the rate of convergence to the origin can be identified by degree of homogeneity, the stability is robust to various perturbations. There are also plenty of researches performed in the last 30 years and the members of *Non-A POST* team extended these notions of homogeneity to discontinuous systems (in a geometric framework), time-delay systems, partial differential equations, time-varying systems, and recently to discrete-time models (together with the concept of local homogeneity). They also proposed plenty of control and estimation algorithms based on homogeneity.

Advantages of homogeneous algorithms taking into account the above mentioned criteria:

A1) The rate of convergence in homogeneous systems can be qualified by its degree (finite-time and fixed-time for negative and positive degrees, respectively).

A2) Due to symmetry of these systems they admit special discretization tools (also developed by the members of *Non-A POST* team), which make simpler they realization for on-line scenarios.

A3) The internal symmetry of these dynamics makes them inherently robust with respect to external perturbations, measurement noises and delays, which is especially important in networked systems.

3.2. Numerical differentiation

Estimating the derivative of a (noisy) signal with a sufficient accuracy can be seen as a key problem in domains of control and diagnosis, as well as signal and image processing. At the present stage of our research, the estimation of the n-th order time derivatives of noisy signals (including noise filtering for $n = 0$) appears as a common area for the whole project, either as a research field, or as a tool that is used both for model-based and model-free techniques. *One of the open questions is about the robustness issues (Indicator 3) with respect to the the parameters and the numerical implementation choices.*

Two classes of techniques are considered here (**Model-based** and **Model-free**), both of them aiming at non-asymptotic estimation.

In what we call *model-based techniques*, the derivative estimation is regarded as an observation problem, which means the software-based reconstruction of unmeasured variables and, more generally, a left inversion problem [1]. This involves linear/homogeneous/nonlinear state models, including ordinary equations, systems with delays, hybrid systems with impulses or switches [2], which still has to be exploited in the finite-time and fixed-time context. Power electronics is already one of the possible applications.

Model-free techniques concern the works initiated by *ALIEN* and *Non-A* teams, which rely on the only information contained in the output signal and its derivatives.

3.3. FT and FxT control and estimation

To design an estimation or control algorithm we have to select a performance criterion to be optimized. Stability is one of the main performance indexes, which has to be established during analysis or design of a dynamical system. Stability is usually investigated with respect to an invariant mode (*e.g.*, an equilibrium, desired trajectory or a limit cycle), then another important characteristics is the time of convergence of the system trajectories to this mode, which can be *asymptotic* (in conventional approaches) or *finite-time* (being the focus of *Non-A POST* team). In the latter case the limit mode has to be exactly established in a finite time dependent on initial deviations (if such a time is independent on initial conditions, then this type of convergence is called *fixed-time*). If the rate of convergence is just faster than any exponential of time, then such a convergence is called *hyperexponential*. The notion of finite-time stability has been proposed in 60s by E. Roxin and it has been developed in many works later, where a particular attention is paid to the time of convergence for trajectories to a steady state (it is worth to note that there exists another notion having the same name, *i.e.* finite-time or short-time stability, which is focused on analysis of a dynamical system behavior on bounded intervals of time, and it is completely different and not considered here). For example, the following simple scalar dynamics:

$$\dot{x}(t) = -|x(t)|^{1+\nu}\mathrm{sign}(x(t)) \quad \forall t \geq 0,\ x(t) \in \mathbb{R},$$

has the solution $x(t) = \beta(|x_0|, t)\mathrm{sign}(x_0)$ for any initial condition $x(0) = x_0 \in \mathbb{R}$, where

$$\beta(s,t) = \begin{cases} \begin{cases} (s^{-\nu} + \nu t)^{-\frac{1}{\nu}} & t < -\frac{s^{-\nu}}{\nu} \\ 0 & t \geq -\frac{s^{-\nu}}{\nu} \end{cases} & -1 \leq \nu < 0 \\ \mathrm{e}^{-t}s & \nu = 0 \\ \frac{s}{(1+\nu s^{\nu} t)^{\frac{1}{\nu}}} & \nu > 0 \end{cases},$$

[1] Left invertibility deals with the question of recovering the full state of a system ("observation") together with some of its inputs ("unknown input observers").

[2] Note that hybrid dynamical systems (HDS) constitute an important field of investigation since, in this case, the discrete state can be considered as an unknown input.

which possesses a finite-time convergence with the settling time $-\frac{|x_0|^{-\nu}}{\nu}$ for $-1 \leq \nu < 0$, an exponential convergence for $\nu = 0$ and the fixed time of convergence to the unit ball is bounded by ν^{-1} for $\nu > 0$. It is straightforward to check that this simple system is homogeneous of degree ν. The members of *Non-A POST* team obtained many results on analysis and design of control and estimation algorithms in this context. A useful and simple method to deal with these three types of convergence (finite-time, fixed-time or hyperexponential) is based on the theory of *homogeneous* systems.

3.4. Applications

The application of the developed control and estimation algorithms for different scenarios in IoT is a priority for *Non-A POST* team. Participation in different potential applications allows the team to better understand the features of IoT and their required performances. A list of possible applications, partially already addressed in the team, is as follows:

- smart bivalve-based biosensor for water quality monitoring (ANR project WaQMoS): presence of persistent external perturbations, which are hard to measure, and important model uncertainty make application of conventional techniques complicated; another issue is consensus seeking between animals for a contamination detection;
- control and estimation for flying vehicles, *e.g.* quadrotors or blimps (1 PhD ONERA, 2 PhDs EC Lille): nonlinearity of the model and its uncertainty coupled with important aerodynamic perturbations have to be compensated by fast (finite- or fixed-time) and robust control and estimation algorithms;
- human behavior modeling and estimation with posterior design of algorithms for human-computer interaction (ANR project TurboTouch): robust finite-time differentiators demonstrate good estimation capabilities needed for prediction in this application;
- human physiological characteristics estimation (like emotion detection, galvanic skin response filtering, fatigue evaluation in collaborations with Neotrope and Ellcie Healthy): intelligent robust filtering and finite-time distributed estimation are key features in this scenario;
- path planning for autonomous vehicles taking into account behavior of humans (PhD CIFRE with SEQUEL team and Renault): application of interval estimation and prediction techniques to treat the uncertainty of the environment by reducing computational complexity of reinforcement learning;
- flow control (in the framework of ContrATech subprogram of CPER ELSAT): the case of control and estimation of a distributed-parameter system with very fast and uncertain dynamics, where finite-time solutions developed by *Non-A POST* team are necessary

Involvement in various real-world scenarios will allow *Non-A POST* to develop demonstrators of disposed technologies with application to IoT.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

- Gabriele Perozzi (a PhD student of the team) get the creativity prize of FR CNRS TTM (La Fédération de Recherche Transports Terrestres & Mobilité);
- Hafiz Ahmed (a former PhD student of the team) is a winner of Annual European PhD Award on Control for Complex and Heterogeneous Systems.

5. New Software and Platforms

5.1. ADHOMFI

Adaptive Homogeneous Filtering

KEYWORDS: Automatic differentiation - Filtering
FUNCTIONAL DESCRIPTION: allows to reconstruct a signal based on derivatives estimation and to filter high amplitude and wide frequencies spectrum perturbations.

- Contact: Denis Efimov

6. New Results

6.1. Implementation of finite- and fixed-time algorithms

In [22] several algorithms of implicit discretization for generalized homogeneous systems having discontinuity only at the origin are developed. They are based on the transformation of the original system to an equivalent one which admits an implicit or a semi-implicit discretization schemes preserving the stability properties of the continuous-time system. Namely, the discretized model remains finite-time stable (in the case of negative homogeneity degree), and practically fixed-time stable (in the case of positive homogeneity degree).

6.2. A solution to finite- and fixed-time estimation

The work [18] deals with the problem of finite-time and fixed-time observation of linear multiple input multiple output (MIMO) control systems. The proposed nonlinear dynamic observers guarantee convergence of the observer states to the original system state in a finite and in a fixed (defined *a priori*) time. Algorithms for the observers parameters tuning are also provided and a robustness analysis against input disturbances and measurement noises is carried out.

6.3. Numeric and analytic design of homogeneous Lyapunov functions

The problem of the synthesis of a homogeneous Lyapunov function for an asymptotically stable homogeneous system is studied in [10]. First, for systems with nonnegative degree of homogeneity, several expressions of homogeneous Lyapunov functions are derived, which depend explicitly on the supremum or the integral (over finite or infinite intervals of time) of the system solutions. Second, a numeric procedure is proposed, which ensures the construction of a homogeneous Lyapunov function.

6.4. Distributed finite-time estimation

In [29] the robust distributed estimation for a class of time-invariant plants is achieved via a finite-time observer, its error reaching zero after a finite time in the absence of perturbation. Two types of robustness are also shown. First, input-to-state stability with respect to measurement noises and additive perturbations is proven. Second, we demonstrate that the estimation error stays bounded in the presence of known transmission delays.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

A transfer contract with Ellcie Healthy on intelligent filtering of measurements in smart eyeglasses.

8. Partnerships and Cooperations

8.1. Regional Initiatives

Non-A POST team hosts CPER Data ControlHub (an on-line laboratory for control system experimentation) and participates at ContrATech subprogram of CPER ELSAT.

8.2. National Initiatives

- Inria Project Lab (IPL) IPL COSY.
- ANR project Finite4SoS (Finite time control and estimation for Systems of Systems), coordinator: W. Perruquetti, 2015-2020.
- ANR project WaQMoS (Coastal waters quality surveillance using bivalve mollusk-based sensors), coordinator: D. Efimov, 2015-2020.
- ANR project TurboTouch (High-performance touch interactions), coordinator: G. Casiez (MJOLNIR team, Inria), 2014-2019.
- ANR project DIGITSLID (DIGITal set-valued and homogeneous SLIding mode control and Differentiators: the implicit approach), coordinator: Bernard Brogliato (TriPOP team, Inria), 2018-2022.
- ANR project ROCC-SYS (Robust Control of Cyber-Physical Systems), coordinator: L. Hetel (CNRS, EC de Lille), 2013-2018.
- We are also involved in several technical groups of the GDR MACS (CNRS, "Modélisation, Analyse de Conduite des Systèmes dynamiques", see http://www.univ-valenciennes.fr/GDR-MACS), in particular: Technical Groups "Identification", "Time Delay Systems", "Hybrid Systems", "Complex Systems, Biological Systems and Automatic Control," and "Control in Electrical Engineering".

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

UCoCoS: the objectives of the project are to create a control-oriented framework for complex systems, and to define a common language, common methods, tools and software for the complexity scientist. The principal investigators are: W. Michiels, J.-P. Richard and H. Nijmeijer.

8.4. International Initiatives

8.4.1. Inria Associate Teams Not Involved in an Inria International Labs

8.4.1.1. HoTSMoCE

Title: Homogeneity Tools for Sliding Mode Control and Estimation

International Partner (Institution - Laboratory - Researcher):

UNAM (Mexico)

Prof. Leonid Fridman

2016–2018

The team *Non-A POST* is developing an estimation theory, built around differential algebra and operational calculation on the one hand, and high gain algorithms (such as sliding mode) on the other hand. The Mexican partner team comes from "Sliding Mode Control" laboratory of UNAM. There exists a strong intersection of interests of both teams (application of homogeneity for design of sliding mode control and estimation algorithms, and analysis of finite-time stability). That is why there exists a long history of collaboration between these two teams. The goal of the project is development of control and estimation algorithms converging in fixed or in finite time by applying the last generation sliding mode techniques and the homogeneity theory. The project realization is planned in the form of short-time visits of permanent staff and visits of PhD students for a long period of stay. Such visits are very important for young scientists, and also help Non-A team to prepare and find good PhDs/post-docs for future.

8.4.2. Inria North European Lab

RECoT, "Robust Estimation and Control with Time Constraints", 2018–2020

International Partner: IBM Research, Dublin (Dr. Sergiy Zhuk)

Non-A Post team of Inria deals with control and estimation of on-line (dynamical) systems with applications to robotics, biological systems, human-machine interfaces and active ow control. The key feature of the developed algorithms is a robustness and a non-asymptotic convergence allowing to fulfill some time constraints. The main methodology is a homogeneity (dilation symmetry) approach. IBM Research team develops minimax algorithms for state estimation and identification of dynamical systems with applications to computational fluid dynamics and image assimilation problems. The key feature of the resulting algorithms is the exact or approximate description of the reachability set of the underlying dynamical system in finite or infinite dimensions. The methodology is relies upon duality and Lyapunov exponents. The objectives of the collaboration are an exchange of the scientific knowledge and the joint research of the following problems: homogeneous observers design using minimax approach; development of fast and consistent computational algorithms for digital implementation of homogeneous controllers and observers; extension of sliding mode control methodology to infinite-dimensional models using minimax approach; the minimax observer-based control design for turbulent flows.

8.4.3. Informal International Partners

- ITMO University, Saint-Petersburg, Russia
- Tel-Aviv University, Tel-Aviv, Israel
- CINVESTAV-IPN, Mexico, Mexico
- Hangzhou Dianzi University, Hangzhou, China
- Brandenburg University of Technology, Cottbus, Germany

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Selection

9.1.1.1. Member of the Conference Program Committees

- Richard J.-P., EUCA-IEEE ECC, Limassol, Cyprus
- Richard J.-P., IFAC TDS, Budapest, Hungary
- Richard J.-P., IARA VEHICULAR, Venice, Italy
- Efimov D., IFAC CHAOS, Eindhoven, Netherlands
- Efimov D., IFAC MICNON, Guadalajara, Mexico

9.1.1.2. Reviewer

The members of the team serve as reviewers to all major conferences in the field: IEEE CDC, ECC, ACC *etc*.

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- Polyakov A., International Journal of Robust and Nonlinear Control
- Polyakov A., Journal of Optimization Theory and Applications
- Efimov D., IFAC Journal on Nonlinear Analysis: Hybrid Systems
- Efimov D., Asian Journal of Control
- Efimov D., IEEE Transactions on Automatic Control

9.1.2.2. Reviewer - Reviewing Activities

The members of the team serve as reviewers to all major journals in the field: IEEE Trans. Automatic Control, Automatica, Systems & Control Letters, SIAM Journal on Optimization and Control, Int. Journal of Robust and Nonlinear Control *etc*.

9.1.3. Research Administration

- Richard J.-P., Investigator for the CNRS FR TTM
- Efimov D., Chair of EECI PhD Award

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

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