



INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Project-Team alien*

*Algebra for Digital Identification and  
Estimation*

*Saclay - Île-de-France, Lille - Nord Europe*

Theme : Modeling, Optimization, and Control of Dynamic Systems

*Activity*  
*R* *eport*

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## **2. Overall Objectives**

### **2.1. History**

After being initiated as a team in **2004**, the project-team ALIEN was created in **2007, July 1st** (see the 2006 activity report for the evolution from the initial group to the present one). Its evaluation was held in March 2009 in the framework of Theme 3 of INRIA (Modeling, Optimization and Control of Dynamic Systems). The Evaluation Committee decided (October 17, 2009) to support ALIEN for the next 4 years. Note that ALIEN was also evaluated in the framework of AERES in Lille, AERES in Saclay, and AERES in Lille-LAGIS CNRS FRE 3303.

### **2.2. Objectives**

The ALIEN project aims at designing new real-time estimation algorithms. Within the huge domain of estimation, ALIEN addresses the following, particular trends: software-based reconstruction of unmeasured variables (also called "observation"), filtering of noisy variables, estimation of the  $n$ -th order time derivatives of a signal, parametric estimation of a linear/nonlinear model (including delay and hybrid systems).

The novelty lies in the fact that ALIEN proposes algebra-based methods, leading to algorithms that are fast (real-time is one of our goals), deterministic (noise is considered as a fast fluctuation), and non-asymptotic (finite-time convergence). This is why we think that ALIEN's studies are shedding a new light on the theoretical investigations around estimation and identification. As it was told, estimation is a huge area. This explains the variety of possible application fields, which both concern signal processing and real-time control. Several cooperations have already been launched on various concrete industrial problems with promising results.

Let us briefly mention some topics which will be studied in this project. In automatic control, we will be dealing with:

- identifiability and identification of uncertain parameters in the system equations, including delays;
- estimation of state variables, which are not measured;
- fault diagnosis and isolation;
- observer-based chaotic synchronization, with applications in cryptography and secure systems.

A major part of signal and image processing is concerned with noise removal, i.e., estimation. Its role in fundamental questions like signal modeling, detection, demodulation, restoration, (blind) equalization, etc, cannot be overestimated. Data compression, which is another key chapter of communication theory, may be understood as an approximation theory where well-chosen characteristics have to be estimated. Decoding for error correcting codes may certainly also be considered as another part of estimation. We know moreover that any progress in estimation might lead to a better understanding in other fields like mathematical finance or biology.

## 2.3. Members complementarity

The members of the ALIEN project work in different places: Paris, Lille, Reims and Nancy; they share the algebraic tool and the non-asymptotic estimation goal, which constitute the natural kernel of the project. Each of them contributes to both theoretical and applied sides of the global project. The following table draws up a scheme of some of their specialities. Of course, *algebraic tools, identification and estimation* are not recalled here since any member of ALIEN is concerned with.

	<i>Upstream Researches</i>	<i>Application Fields</i>
Saclay LIX	Computer algebra - Nonstandard analysis - Signal - Linear & nonlinear control - Delays	
Reims CReSTIC	Signal - Numerical analysis	Denosing - Demodulation - Biomedical signal processing
Cergy ECS	Nonlinear observers - Hybrid systems	Cryptography - Multi-cell chopper/convertor
Lille ENSAM	Applied mathematics	High performance machining - Precision sensors, AFM <sup>1</sup>
Lille LAGIS	Delay systems - Nonlinear control - Observers  (finite-time/unknown input)	Aeronautics - Magnetic bearings - Friction estimation - Networked control - Robotics
Nancy CRAN	Diagnosis - Control - Signal	Industrial processes - Signal & image processing

## 2.4. Highlights

- Patent pending (FR0858532) with EDF on the control of hydroelectric dams.
- Innovation Award 2010 of École Polytechnique for the patent with EDF on the control of hydroelectrical dams.
- Confirmation of the importance of "model-free control" from various concrete examples [44], [45], [57] and [61].
- Jean-Pierre Barbot, with colleagues, creates a working group jointly with MACS (CNRS GDR 717) and DYCOEC (CNRS GDR 2984) on control science and physics ([http://www.univ-valenciennes.fr/GDR-MACS/groupes\\_details.php?gt=SynC](http://www.univ-valenciennes.fr/GDR-MACS/groupes_details.php?gt=SynC)).
- Jean-Pierre Barbot has been nominated for a new term as Invited Professor at Northumbria University, United-Kingdom.
- Mamadou Mboup is nominated as Guest Professor of InnoLecture program at Saarland University, Germany (<http://podcast.univ-reims.fr/videos/?video=MEDIA101019104333990>).
- PEPS/CNRS project: Cédric Join (UHP Nancy -ALIEN), Mamadou Mboup (URCA - ALIEN) and Joachim Rudolph (LSR, Saarland University, Germany).
- Plenary lecture by Lotfi Belkoura at IFAC TDS10 [32].
- Semi-Plenary lecture by Jean-Pierre Barbot at IEEE VSS10 [50].
- Semi-Plenary lecture by Wilfrid Perruquetti at IEEE VSS10 [37].

# 3. Scientific Foundations

## 3.1. Fast parametric estimation and its applications

Parametric estimation may often be formalized as follows:

<sup>1</sup>Atomic Force Microscope, for which fast filtering is required

$$y = F(x, \Theta) + n, \quad (1)$$

where:

- the measured signal  $y$  is a functional  $F$  of the "true" signal  $x$ , which depends on a set  $\Theta$  of parameters,
- $n$  is a noise corrupting the observation.

Finding a "good" approximation of the components of  $\Theta$  has been the subject of a huge literature in various fields of applied mathematics. Most of those researches have been done in a probabilistic setting, which necessitates a good knowledge of the statistical properties of  $n$ . Our project is devoted to a new standpoint which does not require this knowledge and which is based on the following tools, which are of algebraic flavor:

- differential algebra<sup>2</sup>, which plays with respect to differential equations a similar role to commutative algebra with respect to algebraic equations;
- module theory, i.e., linear algebra over rings which are not necessarily commutative;
- operational calculus which was the most classical tool among control and mechanical engineers<sup>3</sup>.

### 3.1.1. Linear identifiability

In most problems appearing in linear control as well as in signal processing, the unknown parameters are *linearly identifiable*: standard elimination procedures yield the following matrix equation

$$P \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_r \end{pmatrix} = Q, \quad (2)$$

where:

- $\theta_i, 1 \leq i \leq r$ , represents an unknown parameter,
- $P$  is a  $r \times r$  square matrix and  $Q$  is a  $r \times 1$  column matrix,
- the entries of  $P$  and  $Q$  are finite linear combinations of terms of the form  $t^\nu \frac{d^\mu \xi}{dt^\mu}$ ,  $\mu, \nu \geq 0$ , where  $\xi$  is an input or output signal,
- the matrix  $P$  is *generically* invertible, i.e.,  $\det(P) \neq 0$ .

### 3.1.2. How to deal with perturbations and noises?

With noisy measurements, the equation (2) becomes:

$$P \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_r \end{pmatrix} = Q + R, \quad (3)$$

<sup>2</sup>Differential algebra was introduced in nonlinear control theory by one of us almost twenty years ago for understanding some specific questions like input-output inversion. It allowed to recast the whole of nonlinear control into a more realistic light. The best example is of course the discovery of *flat* systems which are now quite popular in industry.

<sup>3</sup>Operational calculus is often formalized *via* the Laplace transform whereas the Fourier transform is today the cornerstone in estimation. Note that the one-sided Laplace transform is causal, but the Fourier transform over  $\mathbf{R}$  is not.



where  $R$  is a  $r \times 1$  column matrix, whose entries are finite linear combination of terms of the form  $t^\nu \frac{d^\mu \eta}{dt^\mu}$ ,  $\mu, \nu \geq 0$ , where  $\eta$  is a perturbation or a noise.

### 3.1.2.1. Structured perturbations

A perturbation  $\pi$  is said to be *structured* if, and only if, it is annihilated by a linear differential operator of the form  $\sum_{\text{finite}} a_k(t) \frac{d^k}{dt^k}$ , where  $a_k(t)$  is a rational function of  $t$ , i.e.,  $\left(\sum_{\text{finite}} a_k(t) \frac{d^k}{dt^k}\right) \pi = 0$ . Note that many classical perturbations like a constant bias are annihilated by such an operator. An *unstructured* noise cannot be annihilated by a non-zero differential operator.

By well-known properties of the non-commutative ring of differential operators, we can multiply both sides of equation (3) by a suitable differential operator  $\Delta$  such that equation (3) becomes:

$$\Delta P \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_r \end{pmatrix} = \Delta Q + R', \quad (4)$$

where the entries of the  $r \times 1$  column matrix  $R'$  are unstructured noises.

### 3.1.2.2. Attenuating unstructured noises

Unstructured noises are usually dealt with stochastic processes like white Gaussian noises. They are considered here as highly fluctuating phenomena, which may therefore be attenuated *via* low pass filters. Note that no precise knowledge of the statistical properties of the noises is required.

### 3.1.2.3. Comments

Although the previous noise attenuation<sup>4</sup> may be fully explained *via* formula (4), its theoretical comparison<sup>5</sup> with today's literature<sup>6</sup> has yet to be done. It will require a complete resetting of the notions of noises and perturbations. Besides some connections with physics, it might lead to quite new "epistemological" issues [77].

## 3.1.3. Some hints on the calculations

The time derivatives of the input and output signals appearing in equations (2), (3), (4) can be suppressed in the two following ways which might be combined:

- integrate both sides of the equation a sufficient number of times,
- take the convolution product of both sides by a suitable low pass filter.

The numerical values of the unknown parameters  $\Theta = (\theta_1, \dots, \theta_r)$  can be obtained by integrating both sides of the modified equation (4) during a very short time interval.

### 3.1.4. A first, very simple example

Let us illustrate on a very basic example, the grounding ideas of the ALIEN approach, based on algebra. For this, consider the first order, linear system:

$$\dot{y}(t) = ay(t) + u(t) + \gamma_0, \quad (5)$$

where  $a$  is an unknown parameter to be identified and  $\gamma_0$  is an unknown, constant perturbation. With the notations of operational calculus and  $y_0 = y(0)$ , equation (5) reads:

<sup>4</sup>It is reminiscent to what most practitioners in electronics are doing.

<sup>5</sup>Let us stress again that many computer simulations and several laboratory experiments have been already successfully achieved and can be quite favorably compared with the existing techniques.

<sup>6</sup>Especially in signal processing.

$$s\hat{y}(s) = a\hat{y}(s) + \hat{u}(s) + y_0 + \frac{\gamma_0}{s} \quad (6)$$

where  $\hat{y}(s)$  represents Laplace transform.

In order to eliminate the term  $\gamma_0$ , multiply first the two hand-sides of this equation by  $s$  and, then, take their derivatives with respect to  $s$ :

$$\frac{d}{ds} \left[ s \left\{ s\hat{y}(s) = a\hat{y}(s) + \hat{u}(s) + y_0 + \frac{\gamma_0}{s} \right\} \right] \quad (7)$$

$$\Rightarrow 2s\hat{y}(s) + s^2\hat{y}'(s) = a(s\hat{y}'(s) + \hat{y}(s)) + s\hat{u}'(s) + \hat{u}(s) + y_0. \quad (8)$$

Recall that  $\hat{y}'(s) \triangleq \frac{d\hat{y}(s)}{ds}$  corresponds to  $-ty(t)$ . Assume  $y_0 = 0$  for simplicity's sake<sup>7</sup>. Then, for any  $\nu > 0$ ,

$$s^{-\nu} [2s\hat{y}(s) + s^2\hat{y}'(s)] = s^{-\nu} [a(s\hat{y}'(s) + \hat{y}(s)) + s\hat{u}'(s) + \hat{u}(s)]. \quad (9)$$

For  $\nu = 3$ , we obtained the estimated value  $a$ :

$$a = \frac{2 \int_0^T d\lambda \int_0^\lambda y(t)dt - \int_0^T ty(t)dt + \int_0^T d\lambda \int_0^\lambda tu(t)dt - \int_0^T d\lambda \int_0^\lambda d\sigma \int_0^\sigma u(t)dt}{\int_0^T d\lambda \int_0^\lambda d\sigma \int_0^\sigma y(t)dt - \int_0^T d\lambda \int_0^\lambda ty(t)dt} \quad (10)$$

Since  $T > 0$  can be very small, estimation *via* (10) is very fast.

Note that equation (10) represents an on-line algorithm that only involves two kinds of operations on  $u$  and  $y$  : (1) multiplications by  $t$ , and (2) integrations over a pre-selected time interval.

If we now consider an additional noise, of zero mean, in (5), say:

$$\dot{y}(t) = ay(t) + u(t) + \gamma_0 + n(t), \quad (11)$$

it will be considered as fast fluctuating signal. The order  $\nu$  in (9) determines the order of iterations in the integrals (3 integrals in (10)). Those iterated integrals are low-pass filters which are attenuating the fluctuations.

This example, even simple, clearly demonstrates how ALIEN's techniques proceed:

- they are algebraic: operations on  $s$ -functions;
- they are non-asymptotic: parameter  $a$  is obtained from (10) in finite time;
- they are deterministic: no knowledge of the statistical properties of the noise  $n$  is required.

### 3.1.5. A second simple example, with delay

Consider the first order, linear system with constant input delay<sup>8</sup>:

$$\dot{y}(t) + ay(t) = y(0)\delta + \gamma_0 H + bu(t - \tau). \quad (12)$$

<sup>7</sup>If  $y_0 \neq 0$  one has to take above derivatives of order 2 with respect to  $s$ , in order to eliminate the initial condition.

<sup>8</sup>This example is taken from [69]. For further details, we suggest the reader to refer to it.

Here we use a distributional-like notation where  $\delta$  denotes the Dirac impulse and  $H$  is its integral, i.e., the Heaviside function (unit step)<sup>9</sup>. Still for simplicity, we suppose that the parameter  $a$  is known. The parameter to be identified is now the delay  $\tau$ . As previously,  $\gamma_0$  is a constant perturbation,  $a$ ,  $b$ , and  $\tau$  are constant parameters. Consider also a step input  $u = u_0 H$ . A first order derivation yields:

$$\ddot{y} + a\dot{y} = \varphi_0 + \gamma_0 \delta + b u_0 \delta_\tau, \quad (13)$$

where  $\delta_\tau$  denotes the delayed Dirac impulse and  $\varphi_0 = (\dot{y}(0) + ay(0))\delta + y(0)\delta^{(1)}$ , of order 1 and support  $\{0\}$ , contains the contributions of the initial conditions. According to Schwartz theorem, multiplication by a function  $\alpha$  such that  $\alpha(0) = \alpha'(0) = 0$ ,  $\alpha(\tau) = 0$  yields interesting simplifications. For instance, choosing  $\alpha(t) = t^3 - \tau t^2$  leads to the following equalities (to be understood in the distributional framework):

$$\begin{aligned} t^3 [\ddot{y} + a\dot{y}] &= \tau t^2 [\ddot{y} + a\dot{y}], \\ b u_0 t^3 \delta_\tau &= b u_0 \tau t^2 \delta_\tau. \end{aligned} \quad (14)$$

The delay  $\tau$  becomes available from  $k \geq 1$  successive integrations (represented by the operator  $H$ ), as follows:

$$\tau = \frac{H^k(w_0 + a w_3)}{H^k(w_1 + a w_2)}, \quad t > \tau, \quad (15)$$

where the  $w_i$  are defined, using the notation  $z_i = t^i y$ , by:

$$\begin{aligned} w_0 &= t^3 y^{(2)} = -6 z_1 + 6 z_2^{(1)} - z_3^{(2)}, \\ w_1 &= t^2 y^{(2)} = -2 z_0 + 4 z_1^{(1)} - z_2^{(2)}, \\ w_2 &= t^2 y^{(1)} = 2 z_1 - z_2^{(1)}, \\ w_3 &= t^3 y^{(1)} = 3 z_2 - z_3^{(1)}. \end{aligned}$$

These coefficients show that  $k \geq 2$  integrations are avoiding any derivation in the delay identification.

Figure 1 gives a numerical simulation with  $k = 2$  integrations and  $a = 2, b = 1, \tau = 0.6, y(0) = 0.3, \gamma_0 = 2, u_0 = 1$ . Due to the non identifiability over  $(0, \tau)$ , the delay  $\tau$  is set to zero until the numerator or the denominator in the right hand side of (15) reaches a significant nonzero value.

Again, note the realization algorithm (15) involves two kinds of operators: (1) integrations and (2) multiplications by  $t$ .

It relies on the measurement of  $y$  and on the knowledge of  $a$ . If  $a$  is also unknown, the same approach can be utilized for a simultaneous identification of  $a$  and  $\tau$ . The following relation is derived from (14):

$$\tau(H^k w_1) + a\tau(H^k w_2) - a(H^k w_3) = H^k w_0, \quad (16)$$

and a linear system with unknown parameters  $(\tau, a\tau, a)$  is obtained by using different integration orders:

<sup>9</sup>In this document, for the sake of simplicity, we make an abuse of the language since we merge in a single notation the Heaviside function  $H$  and the integration operator. To be rigorous, the iterated integration ( $k$  times) corresponds, in the operational domain, to a division by  $s^k$ , whereas the convolution with  $H$  ( $k$  times) corresponds to a division by  $s^k/(k-1)!$ . For  $k = 0$ , there is no difference and  $H * y$  realizes the integration of  $y$ . More generally, since we will always apply these operations to complete equations (left- and right-hand sides), the factor  $(k-1)!$  makes no difference.

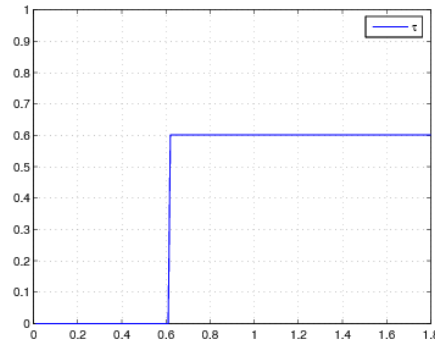


Figure 1. Delay  $\tau$  identification from algorithm (15)

$$\begin{pmatrix} H^2 w_1 & H^2 w_2 & H^2 w_3 \\ H^3 w_1 & H^3 w_2 & H^3 w_3 \\ H^4 w_1 & H^4 w_2 & H^4 w_3 \end{pmatrix} \begin{pmatrix} \hat{\tau} \\ \hat{a}\tau \\ -\hat{a} \end{pmatrix} = \begin{pmatrix} H^2 w_0 \\ H^3 w_0 \\ H^4 w_0 \end{pmatrix}.$$

The resulting numerical simulations are shown in Figure 2. For identifiability reasons, the obtained linear system may be not consistent for  $t < \tau$ .

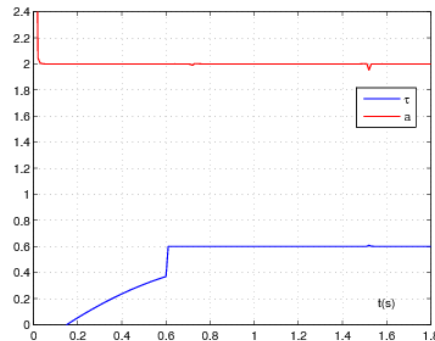


Figure 2. Simultaneous identification of  $a$  and  $\tau$  from algorithm (16)

### 3.2. Numerical differentiation

Numerical differentiation, i.e., determining the time derivatives of various orders of a noisy time signal, is an important but difficult ill-posed theoretical problem. This fundamental issue has attracted a lot of attention in many fields of engineering and applied mathematics (see, e.g. in the recent control literature [70], [71], [86], [85], [89], [90], and the references therein). A common way of estimating the derivatives of a signal is to resort

to a least squares fitting and then take the derivatives of the resulting function. In [93], [91], this problem was revised through our algebraic approach. The approach can be briefly explained as follows:

- The coefficients of a polynomial time function are linearly identifiable. Their estimation can therefore be achieved as above. Indeed, consider the real-valued polynomial function  $x_N(t) = \sum_{\nu=0}^N x^{(\nu)}(0) \frac{t^\nu}{\nu!} \in \mathbb{R}[t]$ ,  $t \geq 0$ , of degree  $N$ . Rewrite it in the well known notations of operational calculus:

$$X_N(s) = \sum_{\nu=0}^N \frac{x^{(\nu)}(0)}{s^{\nu+1}}$$

Here, we use  $\frac{d}{ds}$ , which corresponds in the time domain to the multiplication by  $-t$ . Multiply both sides by  $\frac{d^\alpha}{ds^\alpha} s^{N+1}$ ,  $\alpha = 0, 1, \dots, N$ . The quantities  $x^{(\nu)}(0)$ ,  $\nu = 0, 1, \dots, N$  are given by the triangular system of linear equations:

$$\frac{d^\alpha s^{N+1} X_N}{ds^\alpha} = \frac{d^\alpha}{ds^\alpha} \left( \sum_{\nu=0}^N x^{(\nu)}(0) s^{N-\nu} \right) \quad (17)$$

The time derivatives, i.e.,  $s^\mu \frac{d^\mu X_N}{ds^\mu}$ ,  $\mu = 1, \dots, N$ ,  $0 \leq \mu \leq N$ , are removed by multiplying both sides of Equation (17) by  $s^{-\bar{N}}$ ,  $\bar{N} > N$ .

- For an arbitrary analytic time function, apply the preceding calculations to a suitable truncated Taylor expansion. Consider a real-valued analytic time function defined by the convergent power series  $x(t) = \sum_{\nu=0}^{\infty} x^{(\nu)}(0) \frac{t^\nu}{\nu!}$ , where  $0 \leq t < \rho$ . Approximate  $x(t)$  in the interval  $(0, \varepsilon)$ ,  $0 < \varepsilon \leq \rho$ , by its truncated Taylor expansion  $x_N(t) = \sum_{\nu=0}^N x^{(\nu)}(0) \frac{t^\nu}{\nu!}$  of order  $N$ . Introduce the operational analogue of  $x(t)$ , i.e.,  $X(s) = \sum_{\nu \geq 0} \frac{x^{(\nu)}(0)}{s^{\nu+1}}$ . Denote by  $[x^{(\nu)}(0)]_{\varepsilon_N}(t)$ ,  $0 \leq \nu \leq N$ , the numerical estimate of  $x^{(\nu)}(0)$ , which is obtained by replacing  $X_N(s)$  by  $X(s)$  in Eq. (17). It can be shown [82] that a good estimate is obtained in this way.

Thus, using elementary differential algebraic operations, we derive explicit formulae yielding point-wise derivative estimation for each given order. Interesting enough, it turns out that the Jacobi orthogonal polynomials [98] are inherently connected with the developed algebraic numerical differentiators. A least-squares interpretation then naturally follows [92], [93] and this leads to a key result: the algebraic numerical differentiation is as efficient as an appropriately chosen time delay. Though, such a delay may not be tolerable in some real-time applications. Moreover, instability generally occurs when introducing delayed signals in a control loop. Note however that since the delay is known *a priori*, it is always possible to derive a control law which compensates for its effects (see [96]). A second key feature of the algebraic numerical differentiators is its very low complexity which allows for a real-time implementation. Indeed, the  $n^{\text{th}}$  order derivative estimate (that can be directly managed for  $n \geq 2$ , without using  $n$  cascaded estimators) is expressed as the output of the linear time-invariant filter, with finite support impulse response  $h_{\kappa, \mu, n, r}(\cdot)$ . Implementing such a stable and causal filter is easy and simple. This is achieved either in continuous-time or in discrete-time when only discrete-time samples of the observation are available. In the latter case, we obtain a tapped delay line digital filter by considering any numerical integration method with equally-spaced abscissas.

## 4. Application Domains

### 4.1. Application domains

Rather than being a project linked to a specific domain of application, we can say that ALIEN is a method-driven project. However, one must not forget that applicability remains a guideline in all our research.

Estimation is known to be a huge area, which explains the variety of possible application fields our new methods address. During these first few years, ALIEN's techniques have already generated 3 patents [74], [76], [75] and the one pending with EDF-CIH (FR0858532). It shows their efficiency in various industrial domains, including (see the previous reports):

- Vehicle control (engine throttle [87], lateral and longitudinal velocities [57], stop-and-go [100], tire/road contact condition [103]) with PSA, APEDGE, Mines-ParisTech, INRIA IMARA, Universidad Carlos III (Madrid, Spain), Université Paris Sud;
- Hydroelectric power plants [61], [44] with EDF-CIH (patent pending FR0858532);
- Shape memory actuators [84] with Université de Bretagne Occidentale and ANR MAFESMA;
- Magnetic actuators with Saarland University (Germany);
- Power Electronics [45] with Université du Québec (Trois-Rivières, Canada);
- Aircraft identification [99] with ONERA DCSD;
- Secured communications (chaos-based cryptography [97], [105], [104], CPM demodulation [94]) with CINVESTAV (Mexico), Math. Dept. Tlemcen University (Algeria) and PRISME ENSI-Bourges.
- Image and video processing (denoising [80], edge detection [88]) with INRIA QGAR, compression [81], compressive sensing [28], [49] with CINVESTAV (Mexico) and Whuan University (China).
- More recently, financial engineering [40] with MEREOR Investment Management and Advisory SAS.

## 5. New Results

### 5.1. Model-free control

**Participants:** Michel Fliess, Cédric Join, Samer Riachy.

After the successful implementation of model-free control [73], [78] for several concrete situations in 2009:

- Throttle control for IC engines (with APEDGE and PSA) [87];
- Stop-and-go automotive control strategy (in collaboration with the École des Mines de Paris and PSA) [72], [100], [101];
- Hydroelectrical dams modeling and control (in collaboration with EDF)[44], [61];
- Shape memory actuators (collaboration with the team directed by Prof. E. Delaleau at the École Nationale des Ingénieurs de Brest [83], [84]);

this method makes more exciting achievements in 2010, listed as follows:

- Model-free control involves the design of the so-called "intelligent" PID controllers [73], [79], and a mathematical explanation via "intelligent" PID controllers of the strange ubiquity of PIDs has been developed in [35], and the simulations confirm the superiority of the new intelligent feedback design;
- Delta hedging, which plays a crucial role in modern financial engineering, is a tracking control design for a "risk-free" management. The application of model-free control method to set Delta hedging is reported in [40], which avoids most of the shortcomings encountered with the now classic Black-Scholes-Merton framework;
- "Planar Vertical Take-Off and Landing" (PVTOL) aircraft has been largely studied in the academic literature via various advanced nonlinear control techniques. In [63], the model-free control method was successfully used to easily yield the control strategy for PVTOL;

- The model-free control methodology is applied for the first time to power converters, and in particular to a buck converter, and to a Cuk converter in [45]. We evaluate its performances regarding load and supply variations. Our approach, which utilizes "intelligent" PI controllers, does not require any converter identification while ensuring the stability and the robustness of the control synthesis;
- The longitudinal control of the electrical vehicle is challenging, since the chassis and the engine dynamical equations exhibit complex unknown parameters and/or neglected terms. However, using model-free control approach can bypass those parameter and model uncertainties, without the necessity of identifying them, and it is illustrated by convincing experimental results in [57];
- Automatic water level control for open channels have difficulties to keep good performances for a large range of flow and significant unknown disturbances. [61] and [44] used the model-free control technique for controlling water level of hydroelectric run-of-the river power plants with severe constraints and operating conditions. Numerous dynamic simulations show that with a simple and robust control algorithm, the set-point is followed even in severe operating conditions.

## 5.2. Algebraic estimation

**Participants:** Michel Fliess, Cédric Join, Mamadou Mboup, Wilfrid Perruquetti, Lotfi Belkoura, Olivier Gibaru, Zoran Tiganj, Dayan Liu.

Elementary techniques from operational calculus, differential algebra, and non-commutative algebra lead to a new algebraic approach for estimation and detection. It is investigated in various areas of applied sciences and engineering. The following lists only some applications:

- To detect the change-point of discontinuous signal is challenging, especially for applications requiring on-line detection. The difficulties are stemming from corrupting noises which are blurring the discontinuities, and the combined need of fast calculations for real-time implementation and of reliable detection. [18] presented a new algebraic approach for change-point detection, where numerical experiments illustrated the efficiency of the proposed method;
- Single channel EEG systems are very useful in EEG based applications where real time processing, low computational complexity and low cumbersomeness are critical constrains. These include brain-computer interface and biofeedback devices and also some clinical applications such as EEG recording on babies or Alzheimer's disease recognition. [47] proposed to use the algebraic approach to address the problem of eye blink artifacts detection in such systems. The occurrence of an artifact is modeled as an irregularity which appears explicitly in the time (generalized) derivative of the EEG signal as a delay. Manipulating such delay is easy with the operational calculus and it leads to a simple joint detection and localization algorithm. Comparison of the results on artificially created and real signal leads to conclusions that with detection techniques based on derivative estimation we are able to detect not only eye blink artifacts, but also any spike shaped artifact, even if it is very low in amplitude;
- Algebraic parametric differentiation technique is presented in [68], where the approximation error for this derivative estimation is analyzed, which contains two sources of error: the bias term error and the noise error. The analysis for the noise error of a known noise is given. Especially, the bias term errors are bounded for the minimal estimators and the affine estimators. It was shown that these estimators are more efficient than some improved classical ones;
- Algebraic method is adopted to identify the time delay involved in time-delay systems. Identifiability and algebraic identification of time delay systems are investigated in [32], where on-line algorithms were proposed for both parameters and delay estimation. Based on a distributional technique, these algorithms enable an algebraic and simultaneous estimation by solving a generalized eigenvalue problem. Simulation studies with noisy data and experimental results show the performance of the proposed approach.

- Automobile manufacturers have dedicated enormous efforts on developing intelligent systems for the dynamic performance of road vehicles in the last years. Thus, many systems have been deeply studied in order to increase safety and improve handling characteristics. Most of these systems are based on an efficient transmission of the forces from vehicle wheels to the road surface. Friction is the major mechanism for generating these forces on the vehicle. Unfortunately the road maximum adherence cannot be measured directly. In [48] and [27], the algebraic method is used to estimate it. Instantaneous friction is first computed within this framework. Then, extended braking stiffness concept is exploited to detect which braking efforts allow to distinguish a road type from another. A weighted Dugoff model is used during these "distinguishable" intervals to estimate the maximum friction coefficient. Promising results have been obtained in noisy simulations and real experimentations.

### 5.3. Compressive sensing and its applications

**Participants:** Jean-Pierre Barbot, Lei Yu, Gang Zheng.

Compressive Sensing (CS) is a new sampling theory which allows signals to be sampled at sub-Nyquist rate without loss of information. The following gives a brief description of our recent results:

- To guarantee exact recovery from compressed measurements, one should choose specific matrix, which satisfies the Restricted Isometry Property (RIP), to implement the sensing procedure. In [28], we proposed to construct the sensing matrix with chaotic sequence following a trivial method and proved that with overwhelming probability, the RIP of this kind of matrix is guaranteed. Meanwhile, its experimental comparisons with Gaussian random matrix, Bernoulli random matrix and sparse matrix are carried out and show that the performances among these sensing matrix are almost equal;
- Ordinarily, the compressive sensing matrix is constructed by the Gaussian random one or Bernoulli random one. In [28], we have proved that the typical chaotic sequence - logistic map can be adopted to generate the sensing matrix for CS. In [49], we showed that Toeplitz-structured matrix constructed by chaotic sequence is sufficient to satisfy RIP with high probability. With the Toeplitz-structured Chaotic Sensing Matrix (TsCSM), we can easily build a filter with small number of taps. Meanwhile, we implement the TsCSM in compressive sensing of images.

### 5.4. Observability and observer design for nonlinear systems

**Participants:** Jean-Pierre Barbot, Wilfrid Perruquetti, Lotfi Belkoura, Thierry Floquet, Gang Zheng, Lei Yu, Yang Tian.

Observability analysis and observer design are important issues in the field of control theory. Some recent results are listed below:

- A global finite-time observer was proposed in [23] for nonlinear systems which are uniformly observable and globally Lipschitz. The parameters of the proposed observer can be set once and then will provide finite time convergence whatever the initial conditions. This result is based on a high-gain approach combined with recent advances on finite-time stability using Lyapunov function and homogeneity concepts;
- Concerning the problem of the design sliding mode observers for nonlinear systems subject to unknown inputs, in most approaches, sliding mode observers can be designed under the assumption that the system can be transformed into a specific canonical observable form. Then, the state and the unknown input of the system can be recovered in finite time. In [14], the class of systems for which unknown input sliding mode observers can be designed is enlarged by introducing an extended triangular observable form and a higher order sliding mode observers for which finite time convergence can be shown using Lyapunov stability arguments;



- Roughly speaking, two types of observers exist: full order observer and reduced order one. It is well known that the existence of a full order observer with linear error dynamics implies the existence of a reduced order observer with linear error dynamics, however the reverse is not valid. Moreover, there are no results available for nonlinear systems to provide conditions, under which via a transformation, a reduced order observer with linear error dynamics may be found. In [54] and [31], we presented a new nonlinear canonical form which allows us to design reduced order observers, just like the linear case. Necessary and sufficient conditions are given to guarantee the existence of the proposed nonlinear canonical form;
- The problem of loss of observability at low frequency range for the Permanent Magnet Synchronous Motor is always recognized in experimental settings. [51] analyzed the observability for sensorless control design. Moreover, an Estimator/Observer Swapping system is designed for the surface Permanent Magnet Synchronous Motor to overcome position observability problems at zero speed, which becomes unobservable at this point;
- Using the second order sliding mode observer for the induction motor without mechanical sensor was presented in [64] and [46]. This observer converges in finite time and is robust to the variation of parameters. The simulation results show the performance of the proposed observer. Furthermore, an industrial application is presented in order to highlight the technological interest of the proposed method and also show the difficulties due to real time computation constraints;
- By taking the hybrid behavior of the multicellular converter into account, [37] proposed a nonlinear finite time observer to estimate the capacitor's voltages. The stability and properties of the proposed homogeneous finite time observer are studied using Lyapunov theory. Our approach enables the stabilization of the observation errors in spite of the presence of perturbations. Simulations highlight the efficiency of the proposed strategy;
- A robust control for a stepper motor with no position nor velocity sensors and only needing current and voltage measurements was designed in [58] and [39]. Second order sliding mode observers are realized to estimate both rotor angular position and velocity. Moreover, a robust control law, which is also based on second order sliding modes and which uses the estimates of the observer, is designed. The stability of the observer based control loop is discussed. The results obtained in simulations indicate the usefulness and the robustness of the method.

## 5.5. Time-delay systems

**Participants:** Jean-Pierre Richard, Jean-Pierre Barbot, Thierry Floquet, Gang Zheng, Lei Yu.

- Causal and non-causal observability were discussed in [53] for nonlinear time-delay systems. By extending the Lie derivative for time-delay systems in the algebraic framework introduced by [102], we present a canonical form and give sufficient condition in order to deal with causal and non-causal observations of state and unknown inputs of time-delay systems. The problem of causal observability of the states and unknown inputs of nonlinear time-delay systems is investigated in [52]. Algorithms are provided to check the possibility of obtaining causal estimations of the states and unknown inputs for the studied systems;
- Identification problem for systems with delayed inputs was studied in [22], where a fast identification algorithm is proposed. It is based on a non-asymptotic distributional estimation technique initiated in the framework of systems without delay. Such technique leads to simple realization schemes, involving integrators, multipliers and piecewise polynomial or exponential time functions. Thus, it allows for a real time implementation.
- In relation with the framework of embedded and networked systems, the sampled-data stabilization of linear time-invariant systems with feedback delay was considered in [42], where the delay is assumed to be time-varying and that its value is approximatively known. Interval time-varying delay systems was studied in [43], where the time-delay interval is divided into several zones and the systems switch among the different zones. An additional result on the stabilization of neutral systems in the presence of time-varying delays and control saturation was presented in [21].

## 5.6. Multi-dimensional differentiation

**Participants:** Samer Riachy, Mamadou Mboup, Jean-Pierre Richard.

Multivariate signals are abundant in various branches of physics, in telecommunication, geology, econometrics as well as digital images and videos. Online differentiation of multivariate signals in a noisy environment was developed in [62] and [55] by extending further the mono-dimensional differentiation method of [91] and its multidimensional extension [95]. The multivariate estimators enjoy the same properties of their mono-variable counterpart. Namely:

- pointwise estimation,
- orthogonal projection in the orthogonal set of multivariate Jacobi polynomials.

In fact those estimators correspond to orthogonal projection in a Jacobi basis i.e., a least squares minimization. In addition they can be implemented as finite impulse digital filters. We combine somehow optimization and fast computation.

A "fast" practical implementation through a discrete convolution was also developed. The utility of our estimators in image and video processing will be investigated in the future project. We plan to develop new low level image analysis tools for features extraction (edges, motion detection and estimation...).

## 5.7. Hybrid dynamical systems

**Participants:** Jean-Pierre Barbot, Wilfrid Perruquetti, Lotfi Belkoura, Thierry Floquet, Gang Zheng, Lei Yu, Yang Tian.

Concerning hybrid dynamical systems, we obtained the following results:

- The observability of a class of switched systems with Zeno phenomenon or high switching frequency was discussed in [29], where three observability forms are proposed and the observability for each form with knowledge of filtered switching signal is analyzed. Meanwhile, sufficient and necessary conditions for the existence of a diffeomorphism to transform a class of switched systems into one of such forms are presented. Examples and simulations are given at the end to highlight the theoretical results;
- A method for the finite time estimation of the switching times in linear switched systems was proposed in [26]. This approach is based on algebraic tools and distribution theory. Switching time estimates are given by explicit algebraic formulae that can be implemented in a straightforward manner using standard tools from computational mathematics. Simulations illustrate the efficiency of the proposed techniques;
- On-line identification of nonlinear continuous-time systems subject to impulsive terms was studied in [15]. Using a distribution framework, a scheme is proposed in order to annihilate singular terms in differential equations representing a class of impulsive systems. As a result, an on-line estimation of unknown parameters is provided, regardless of the switching times nor of the impulse rules. Numerical simulations of physical processes with noisy data are illustrating our methodology and results;
- Traditional method to design a controller for each subsystem of switched systems will increase the complexity of the controller's realization. Sufficient conditions for designing a uniform output feedback controller for linear switched systems was given in [30], and this common controller can be used for all subsystems of the switched systems. Then the output stabilization problem for a particular class of linear switched systems under this uniform output feedback controller has been studied. An illustrative example is given in order to highlight the proposed method.

## 5.8. Atomic force microscope

**Participants:** Olivier Gibaru, Wilfrid Perruquetti, Dayan Liu, Stéphane Thiery.

An Atomic Force Microscope (AFM) is a three-axis  $(x, y, z)$  system used to capture images or to manufacture at micro and nano scale. The main features of this work is to improve the abilities of an AFM to capture image at fast speed and at the same time to improve the accuracy of trajectory tracking.

By using the model-free control method and the algebraic estimation approach, we have obtained the following results:

- Modelisation of AFM has been studied, based on which the model-free control method has been tested and compared to the classical PID method. The simulation showed that the proposed method with i-PID is better than the one with PID.
- In practice, the model-free control approach has been applied, with success, to control a piezoelectric actuator of AFM in LNE ("Laboratoire National de métrologie et d'Essais"), located at Trappes. Future experiments would be realized in Lille.

The collaboration with the MEC (Manufacturing Engineering Center) of Cardiff University is established on AFM probe-based nano mechanical machining. Moreover, a nano positioning system is now available at Arts et Metiers ParisTech center of Lille, and we have begun to develop new planning method by programming path planning trajectory on this  $(x, y)$  nano positioning system of  $75\mu m$  range of motion.

## 6. Contracts and Grants with Industry

### 6.1. Contracts with Industry

- Contract with EDF-CIH (Centre d'Ingénierie Hydraulique) to study control and estimation problems in hydroelectrical dams;
- Contract with DIRIF (Direction Interdépartementale des Routes d'Île-de-France) to control the highway access problem.

## 7. Other Grants and Activities

### 7.1. Regional Initiatives

- Grant from GRAISyHM (Groupement de Recherche en Automatisation Intégrée et Systèmes Homme-Machine, governmental Federation and Regional Council) on networked control (results connected with delay systems), with LAGIS and LAMIH (CNRS-UVHC Valenciennes).

### 7.2. National Initiatives

- We are 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" and "Control in Electrical Engineering".
- Model-free control: collaborations with Professor Brigitte D'Andréa-Novel at Mines ParisTech and Professor Emmanuel Delaleau at ENIB.
- Atomic Force Microscope (AFM): application of new algebraic methods in tapping mode for AFM, collaboration with the National Laboratory of Metrology (LNE) located at Trappes.

### 7.3. European Initiatives

- Thierry Floquet and Joachim Rudolph, from Saarland University (Germany), co-supervised a Master student in spring 2009. Since October 2009, they have been co-supervising a PhD student on the problem of fast identification and closed-loop control for magnetic shaft.
- Collaboration with Emmanuel Brousseau of Cardiff University for the project: "on nano mechanical machining of 3D nano structures by AFM".

## 7.4. International Initiatives

- Collaboration with Emilia Fridman (Tel Aviv University, Israel) and Joao Manoel Gomes da Silva (UFRGS, Porto Alegre, Brazil) on time-delay systems.
- Co-supervision (French "co-tutelle") of the PhD thesis of Kaouther Ibn Taarit with Mekki Ksouri, ENIT Tunis, Tunisia, on pseudo-spectra for delay identification.
- Collaboration with Hong Sun (Whuan University, China) for co-supervising the PhD thesis of Lei Yu on Compressive sensing.
- Collaborations with Guiseppe Fedele from University of Calabria, Italy, on "Model-free control".
- Programme Hubert Curien VOLUBILIS (Maroc, Integrated Action MA/09/211) between LAGIS (Université Lille1), ALIEN INRIA and Laboratory of Electronic, Information and Biotechnology of Department of Science at University Moulay Ismail of Meknès.

## 8. Dissemination

### 8.1. Animation of the scientific community

#### 8.1.1. Editorial boards

- Michel Fliess is currently Associate Editor of *Forum Mathematicum* and *Journal of Dynamical and Control Systems*.
- Jean-Pierre Richard is currently Associate Editor of *Int. J. of Systems Science*.
- Mamadou Mboup is currently Managing Editor of *African Diaspora Journal of Mathematics*.
- Thierry Floquet is currently Associate Editor of *e-sta*.

#### 8.1.2. Program Committees

- IFAC Technical Committees: The members of ALIEN are participating to several technical committees of the IFAC (International Federation of Automatic Control, see the TC list on <http://www.ifac-control.org/areas>): TC 1.3 - Discrete Event and Hybrid Systems, TC 1.5 Networked Systems, TC 2.2 Linear Control Systems, TC 2.3 Nonlinear Control Systems, TC 2.5 Robust Control.
- CIFA 2010: Jean-Pierre Richard is the president of international program committee and the chairman of session "emergent domains". Wilfrid Perruquetti is the chairman of session "hybrid dynamic systems". Michel Fliess, Jean-Pierre Barbot, Mamadou Mboup, Lotfi Belkoura and Thierry Floquet are involved in the international program committee.
- Jean-Pierre Richard was in the International Program Committee of several IEEE and IFAC conferences: IEEE International Conference on Communications, 2011; IEEE International Workshop Towards Smart Communications and Network technologies applied on Autonomous Systems, 2010; IFAC Workshop on Distributed Estimation and Control of Networked Systems, 2010; IEEE Mediterranean Conference on Control and Automation, 2010; IFAC Symposium on System Structure and Control, 2010;
- Jean-Pierre Barbot was in the committee of IEEE International Workshop on Variable Structure Systems, 2010.

- Mamadou Mboup was in the committee of IEEE International Workshop on Machine Learning for Signal Processing, 2010, and in committee of IEEE International Telecommunication Symposium, 2010.
- Gang Zheng was in the committee of IEEE International Conference on Intelligent Control and Information Processing, 2010.

### 8.1.3. Scientific and administrative responsibilities

- Jean-Pierre Richard is president of the GRAISyHM, federation from the French government. He is an expert for the evaluation of projects submitted to ANR, CNRS, DGRI and AERES, and heading the 3rd year professional training "Research" of the École Centrale de Lille.
- Wilfrid Perruquetti is an expert for the evaluation of ANR program Blanc SIMI (2009-2010). From 2010, he is the scientific head of this ANR program.
- Mamadou Mboup is heading the group SYSCOM - CReSTIC, University of Reims Champagne-Ardenne.
- Lotfi Belkoura is heading the Master "AG2i: Automatique, Génie Informatique et Image", University of Lille 1 and École Centrale de Lille. This Master, after a national evaluation (A), is presently "SMaRT: Systèmes, Machines autonomes et Réseaux de Terrain" (see <http://master-ase.univ-lille1.fr/index.php?page=organisation-3>).
- Thierry Floquet is an expert for the evaluation of projects submitted to Israel Science Foundation.
- The team members are also involved in numerous examination committees of theses and Habilitations, in France and abroad.

### 8.1.4. Stay

- From February to July 2010, Mamadou Mboup was Guest Professor at Saarland University, InnoLecture program, Germany.
- From June to July 2010, Stéphane Thierry was at Cardiff University, United-Kingdom.

### 8.1.5. Visitors

- Yuri Orlov, Research director at CISES, Ensenada, Mexico, June 2010, invited by École Centrale de Lille.
- Emilia Fridman, Professor, Tel Aviv University, Israel, June 2010, invited by École Centrale de Lille.

### 8.1.6. Participation to conferences, seminars

- IEEE Conférence Internationale Francophone d'Automatique, Nancy, France, June 02-04, 2010. (Most members of ALIEN).
- IEEE, IET International Symposium on Communication Systems, Networks and Digital Signal Processing, Newcastle, United-Kingdom, July 21-23, 2010. (Jean-Pierre Barbot, Gang Zheng).
- IEEE International Workshop on Variable Structure Systems, Mexico City, Mexico, June 26-28, 2010. (Jean-Pierre Barbot, Wilfrid Perruquetti).
- IFAC Symposium on Nonlinear Control Systems, Bologna, Italy, September 01-03, 2010. (Michel Fliess, Jean-Pierre Barbot, Thierry Floquet).
- IFAC Symposium on System, Structure and Control, Ancona, Italy, September 15-17, 2010. (Michel Fliess).
- IEEE Conference on Decision and Control, Atlanta, USA, December 15-17, 2010. (Jean-Pierre Barbot).
- IFAC Workshop on Time Delay Systems, Prague, Czech Republic, June 7-9, 2010. (Lotfi Belkoura).

- Jean-Pierre Richard was a guest lecturer and presented surveys on Time Delay Systems and Networked Control Systems: in Besançon, by the GDR DYCOEC: A delay, what does it change? Seminar of the GDR DYCOEC, FEMTO LAB Besançon, France, 9 November 2010; and in Tunis, by ENSI and ENIT: Contrôle à travers le réseau : questions générales, résultats récents, Seminar ENSI-ENIT, École Nat. des Sciences de l'Informatique, École Nat. d'Ingénieurs de Tunis, Tunisia, 10 February 2010.

### 8.1.7. Reviews

The members of ALIEN are reviewers for most of the journal of the control and signal communities: IEEE Transactions on Automatic Control, IEEE Transactions on Systems and Control Technologies, IEEE Transactions on Industrial Electronics, IEEE Transactions on Signal Processing, Automatica, Systems & Control Letters, International Journal of Control, International Journal of Robust and Nonlinear Control, International Journal of Systems Science, Journal Européen des Systèmes Automatisés, IET Control Theory & Applications, Fuzzy Sets and Systems, Mathematics and Computers in Simulation, International Journal of Modeling and Simulation, Journal of the Franklin Institute, ...

### 8.1.8. Theses and Habilitations

- Yang Tian, "Contribution on observation and estimation of linear systems", December 8, 2010.
- Kaouther Ibn Taarit, "Contribution on identification of time-delay systems", December 17, 2010.

## 8.2. Teaching

The members of the team teach at different level in universities and engineering schools and, in particular, at Master Thesis level:

Name	Course title	Level	Institution
Barbot	Process Control	Master	Univ. Tlemcen, Algeria
Fliess	Advanced control	Master	École polytechnique, Tunis
Gibaru	Applied Mathematics	Master	USTL-UVHC-ULCO
Mboup	Advanced Signal Processing	Master	Univ.Paris 5, ENIT-Tunis
Perruquetti	Nonlinear control	SMART	EC Lille - USTL
Richard	Mathematical tools for nonlinear systems	Master AG2i	EC Lille - USTL
Richard	Dynamical systems	Research training	EC Lille
Belkoura	An introduction to distributions	Master AG2i	EC Lille - USTL

- Jean-Pierre Richard is in charge of the professional training "Research" of École Centrale de Lille since 2003 (training for last-year students of EC Lille who are preparing a research career). ([http://www.ec-lille.fr/85787934/0/fiche\\_\\_\\_pagelibre/](http://www.ec-lille.fr/85787934/0/fiche___pagelibre/)).
- Lotfi Belkoura is in charge of the SMART Master Thesis training in control of University of Lille 1 and École Centrale de Lille.
- Jean-Pierre Barbot is in charge of the Master Thesis training in control of the University of Tlemcen, Algeria.

## 9. Bibliography

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