INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# *Project-Team ALIEN*

# *ALgèbre pour Identification et Estimation Numériques*

*Futurs*

THEME NUM

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# 1. Team

**Head of project-team**

Michel Fliess [ Research Director CNRS, HdR ]

**Vice-head of project team**

Mamadou Mboup [ Associate professor, Université René Descartes, UFR de mathématiques et informatique, CRIP5, Paris, HdR ]

Jean-Pierre Richard [ Professor, École Centrale de Lille & Laboratoire LAGIS, CNRS UMR 8146, HdR ]

**administrative assistant**

Nicole Dubois [ Assistante ingénieure CNRS ]

**Reserch scientists (external)**

Jean-Pierre Barbot [ Professor, ENSEA Cergy-Pontoise, Laboratoire ECS-EA 3649, HdR ]

Lotfi Belkoura [ Associate Professor Université des Sciences et Technologies de Lille & Laboratoire LAGIS UMR 8146, HdR ]

Thierry Floquet [ Research Scientist CNRS, Laboratoire LAGIS UMR 8146, École Centrale de Lille ]

Cédric Join [ Assistant professor Université Henry Poincaré, Nancy ]

François Ollivier [ Research Scientist CNRS, Laboratoire LIX, École polytechnique ]

Wilfrid Perruquetti [ Professor, École Centrale de Lille & Laboratoire LAGIS UMR 8146, HdR ]

Alexandre Sedoglavic [ Assistant professor Université des Sciences et Techniques de Lille ]

**PHD Students**

Philipp May [ Universität der Bundeswehr, Munich. Supervisors: C. Join (Nancy) and Johann Reger (Munich). Subject: Diagnosis. Support: German Ministry of Defence ]

Samer Riachy [ Ecole Centrale de Lille, started September 2005. Supervisors: J.-P. Richard and L. Belkoura. Subject: Friction compensation. Support: French Ministry of Research ]

# 2. Overall Objectives

## 2.1. General presentation

**Keywords:** *control*, *estimation*, *identification*, *signal processing*.

The present project is an evolution from the initial *INRIA Futurs* action (ALIEN, February 2004) regrouping the following five researchers: Michel FLIESS, Polytechnique; Cédric JOIN, Nancy; Mamadou MBOUP, Paris V; François OLLIVIER, Polytechnique; Alexandre SEDOGLAVIC, Lille. The five following colleagues joined ALIEN in 2006: Jean-Pierre BARBOT, Cergy-Pontoise; Lotfi BELKOURA, Lille; Thierry FLOQUET, Lille; Wilfrid PERRUQUETTI, Lille; Jean-Pierre RICHARD, Lille.

As before the members of the new ALIEN are distributed between 3 locations: Paris, Lille and Nancy. In the new team there is a perfect balance between members working in the Paris and Lille areas, whereas in the old one Paris had a clear majority.

Besides the notable reenforcement of the ALIEN's research potential from 5 to 10 permanent researchers, this reasoned evolution both corresponds to:

- An upholding of the initial scientific objectives: The project still aims at developing upstream researches in fast identification and estimation, as well as concrete applications to signal (including image, video and fault detection) and control (including real-time control and diagnosis).
- A broadening of the potential applications: Whereas the objectives remain unchanged, the class of workable models is enlarged, in particular, to time-delay systems and variable structure ones. Let us first recall some of the signal-oriented applications already present in the original project: Denoising, demodulation, compression of mono- or multi-dimensional signals, break detection... Roughly speaking, the recently opened applications are a bit more “control-oriented”: High-speed or high-precision mechanical devices (*via* active magnet bearings or friction compensation); Embedded systems (networked control, cooperative robotics); Aeronautics (flight model identification)...

All the ALIEN participants are invested in both theoretical advances and application-oriented ones. All of them share the algebraic tool and the non-asymptotic estimation aim, which constitutes the natural kernel of the project and was already grounding ALIEN 1. However, ALIEN 2 will take advantage of the various participants backgrounds and favourite domains, the complementarity of which is going to be depicted in the following subsection.

So, each of the ALIEN members contributes to both theoretical and applied sides of the global project. Even if it is not possible to clearly distinguish between the future contributions of each one, it is possible to draw up a scheme of some of the specialities. Of course, *algebraic tools, identification and estimation* are not recalled here since everybody in ALIEN is concerned with.

| | *Upstream Researches* | *Application Fields* |
|---|---|---|
| Saclay LIX | Computer algebra - Nonstandard analysis - Signal Linear & nonlinear control - Delays | |
| Paris 5 | Signal processing - Numerical analysis | Digital communications, Signal denoising, Industrial processes |
| Cergy ECS | Nonlinear observers - Hybrid systems | Cryptography - Multi-cell chopper/converter |
| Lille LIFL | Computer algebra | Biology - Dedicated software |
| Lille LAGIS | Delay systems - Nonlinear control - Observers(finite-time/unknown input) | Magnet bearing - Frictions - Robotics - Aeronautics |
| Nancy CRAN | Diagnosis - Control - Signal | Industrial processes - Signal & image processing |

## 2.2. Introduction

### 2.2.1. Parametric estimation and its application

Parametric estimation may often be formalized as follows:

$$y = F(x, \Theta) + n, \tag{1}$$

where:

- the observed 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[1] is devoted to a new standpoint which does not require this knowledge and which is based on the following tools, which are of algebraic flavour:

- differential algebra[2], 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[3].

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[1] Our works in this domain are already benefiting from: two *Actions Spécifiques* of the CNRS (RTP 24), one in control and the other in signal; one *Equipe Projet Multi-Laboratoire* of the CNRS (RTP 55), on control over networks; two *Math-STIC* programs from the CNRS.

[2] 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.

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.

A major part of signal and image processing is concerned with noise removal, i.e. estimation. Its role in fundamental questions like signal modelling, detection, demodulation, restoration, (blind) equalisation, 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.

People involved in this project are working either in:

- control or signal,
- (applied) algebra.

This unusual mixture is easily explained as follows:

- Most methods which are utilised are of algebraic flavour.
- Recent techniques – introduced and developed in particular by some members of this project for solving systems of polynomial equations (see publications of the group TERA[4]) – can be imported to improve the estimation algorithms which are of algebraic nature.
- These algorithms have to be implemented in a computer algebra system, to take advantage of their algebraic nature, and run as preprocessing before a final numerical treatment.

Studies related in one way or the other to identification and estimation are of course well represented at INRIA. An exceptional cooperation is already existing between some of us and the SOSSO project on questions pertaining to mathematical modelling in biology. The rich intellectual atmosphere of INRIA will most certainly facilitate cross fertilisation with other groups. The strong ties of INRIA with the industrial world will moreover yield an easier access to applications.

### 2.2.2. *A first, very simple example*

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

$$\dot{y}(t) = ay(t) + u(t) + \gamma_0, \tag{2}$$

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 (2) reads:

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

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[3] Operational calculus is often formalised *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.

[4] http://tera.medicis.polytechnique.fr/tera/pub.html

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 $s$ :

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

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

Recall that $\hat{y}'(s) \triangleq \frac{d\hat{y}(s)}{ds}$ corresponds to $-ty(t)$. Assume $y_0 = 0$ for simplicity's sake[5]. Then, for any $\nu > 0$,

$$s^{-\nu}\left[2s\hat{y}(s) + s^2\hat{y}'(s)\right] = s^{-\nu}\left[a(s\hat{y}'(s) + \hat{y}(s)) + s\hat{u}'(s) + \hat{u}(s)\right]. \tag{3}$$

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

$$a = \frac{2\int_0^T d\lambda \int_0^\lambda y(t)dt - \int_0^T ty(t)dt + \int_0^T d\lambda \int_0^\lambda tu(t)dt - \int_0^T d\lambda \int_0^\lambda d\sigma \int_0^\sigma u(t)dt}{\int_0^T d\lambda \int_0^\lambda d\sigma \int_0^\sigma y(t)dt - \int_0^T d\lambda \int_0^\lambda ty(t)dt} \tag{4}$$

Since $T > 0$ can be very small, estimation *via* (4) is very fast.

Note that equation (4) 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 (2), say:

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

it will be considered as fast fluctuating signal. The order $\nu$ in (3) determines the order of iterations in the integrals (3 integrals in (4)). 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 (4) in finite time;
- they are deterministic: no knowledge of the statistical properties of the noise $n$ is required.

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

Now, let us consider the first order, linear system with constant input delay[6]:

$$\dot{y}(t) + ay(t) = y(0)\delta + \gamma_0 H + bu(t - \tau). \tag{6}$$

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[5] 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.

[6] This example is taken from [22]. 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)[7]. Still for simplicity, we suppose now that 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:

$$\ddot{y} + a\dot{y} = \phi_0 + \gamma_0\,\delta + b\,u_0\,\delta_\tau, \tag{7}$$

where $\delta_\tau$ denotes the delayed Dirac impulse and $\phi_0 = (\dot{y}(0) + ay(0))\,\delta + y(0)\,\delta^{(1)}$, 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):

$$\begin{array}{rcl} t^3\,[\ddot{y} + a\dot{y}] & = & \tau\,t^2\,[\ddot{y} + a\dot{y}], \\ bu_0\,t^3\delta_\tau & = & bu_0\,\tau\,t^2\delta_\tau. \end{array} \tag{8}$$

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

$$\tau = \frac{H^k(w_0 + a\,w_3)}{H^k(w_1 + a\,w_2)}, \qquad t > \tau, \tag{9}$$

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

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

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 denominator in the right hand side of (9) reaches a significant nonzero value.

Again, note the realization algorithm (9) 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 (8):

$$\tau(H^k w_1) + a\,\tau(H^k w_2) - a\,(H^k w_3) = H^k w_0, \tag{10}$$

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

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[7] In this document, in order to keep things simple, 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.

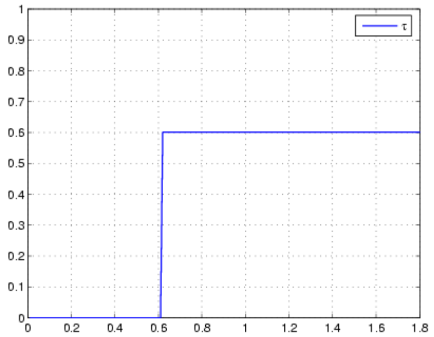

*Figure 1. Delay $\tau$ identification from algorithm (9)*

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

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

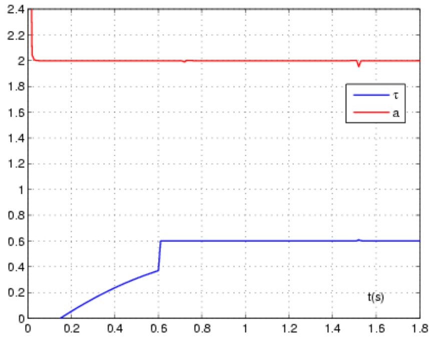

*Figure 2. Simultaneous identification of a and $\tau$ from algorithm (10)*

# 3. Scientific Foundations

## 3.1. Identifiability

Parameter identification is a key step in modelling. When trying to describe a process by differential equations, the validation of a model implies to be able to compute a set of parameters allowing to product a theoretical behaviour corresponding to experimental data. A preliminary issue is to study *identifiability* which means that there is a unique set of parameters corresponding to a given behaviour of the system.

### 3.1.1. Algebraic elimination

For algebraic differential systems, identifiability may be tested in various ways, especially those stemming from differential algebra. In many cases, one can replace the input-output behaviour of the system by some polynomial or rational mapping. Testing identifiability reduces then to test the injectivity of that mapping. One can also reduce the problem to that of testing algebraic dependence of the parameters on the differential field generated by the inputs and outputs. This may be done by characteristic set computations.

Although those algebraic tools have made great progress during the last decade, the intrinsic complexity of those elimination tools is exponential in the generic case, for one has to express the relations of algebraic dependence, whose size is exponential.

One could expect to escape from this trouble by choosing to represent polynomials not as a sum of monomials but as a program computing them. It has been a fruitful approach for solving algebraic systems.

### 3.1.2. Towards fast local computations

Another solution is to restrict oneself to *local* identifiability, requiring the set of parameters to be unique not on the whole space but only on some open neighbourhood. This allows to test identifiability in polynomial time, for one only has to compute the rank of Jacobian matrices. The Maple package of A. Sedoglavic[8] is able to test identifiability of systems with five state variables and seventeen parameters in about ten seconds on some regular PC. Moreover, if the considered system is not identifiable, the package can also compute in many cases groups of symmetries leaving the input and output invariant. This is of great help in order to construct an identifiable model with a different choice of parameters.

### 3.1.3. Modelling in biology

This approach has already been of great help in biology. A. Sedoglavic was able to show that some model describing the action of an antibiotic was not identifiable. The computation of a one parameter group of symmetry has shown that the blood volume could not be computed. This suggested a new identifiable model by taking the blood volume as a unit, the exact knowledge of this volume being unimportant for studying the efficiency of the antibiotherapy.

## 3.2. Fast estimation

### 3.2.1. Linear identifiability

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

$$P \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_r \end{pmatrix} = Q, \tag{11}$$

where:

- $P$ 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., $\det(P) \neq 0$.

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

With noisy measurements equation (11) becomes:

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[8] Available at url: http://www2.lifl.fr/ sedoglav/Software/ObservabilityTest/

$$P\begin{pmatrix}\theta_1\\ \vdots\\ \theta_r\end{pmatrix} = Q + R, \tag{12}$$

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.

#### 3.2.2.1. 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 noncommutative ring of differential operators, we may multiply both sides of equation (12) by a suitable differential operator $\Delta$ such that equation (12) becomes:

$$\Delta P\begin{pmatrix}\theta_1\\ \vdots\\ \theta_r\end{pmatrix} = \Delta Q + R', \tag{13}$$

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

#### 3.2.2.2. 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.

#### 3.2.2.3. Comments

Although the previous noise attenuation[9] may be fully explained *via* formula (13), its theoretical comparison[10] with today's literature[11] has yet to be done. It will necessitate a complete resetting of the notions of noises and perturbations. Besides some connections with physics, it might lead to quite new "epistemological" issues [15].

### 3.2.3. Some hints on the calculations

The time derivatives of the input and output signals appearing in equations (11), (12), (13) may be suppressed in the two following ways which might be combined:

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

Obtaining the numerical values of the unknown parameters $\Theta = (\theta_1, \cdots, \theta_r)$ may be achieved by integrating both sides of the modified equation (13) during a very short time interval.

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[9] It is reminiscent to what most practitioners in electronics are doing.

[10] Let us stress again that many computer simulations and several laboratory experiments have been already successfully achieved and may be quite favorably compared with the existing techniques.

[11] Especially in signal processing.

### 3.2.4. Time derivatives of noisy signals

Determining derivatives of various orders of a noisy time signal is a fundamental issue, which has been often tackled in signal processing as well as in automatic control. We have recently proposed a quite efficient solution which may be explained as follows:

- The coefficients of a polynomial time function are linearly identifiable. Their estimation can therefore be achieved as above.
- For an arbitrary analytic time function, apply the preceding calculations to a suitable truncated Taylor expansion.

### 3.2.5. Delay identification

As we have seen in the introductive example of subsection 2.2.3, the framework of convolution equations can be used for fast identification issues and leads to computations analogous to the algebraic framework (multiplications by $t$ and integrations). This link was pointed out for the first time in our communication: “On-line identification of systems with delayed inputs" (Belkoura, Richard & Fliess 2006) [22]. Further works will extend this first result within both the algebraic and distributional formalisms.

In the case of systems with one delay, we achieved the identification of both unknown parameters and delay by using, as a starting point, an eigenvalue problem of the form:

$$(P_1 + \tau P_2)\Theta = 0,$$

where the unknown delay $\tau$ and parameters $\Theta = (\theta_1, ..., \theta_r, 1)^T$ are identified as the constant pair eigenvalue/eigenvector. In case of delayed and piecewise constant inputs, matrices $P_1$ and $P_2$ share the same structure as the above linear problem, while for general input and/or state delay, convolution products are required. Numerical simulations as well as experimental results have shown the feasibility of the proposed technique.

# 4. Application Domains

## 4.1. Control applications

### 4.1.1. Closed loop identification

In many practical situations, parameter identification has to be achieved in real time, i.e., in closed loop while the plant is working. This most important problem remains largely open, even for simple and elementary linear systems. Our method allows to achieve closed loop identification even for nonlinear systems[12].

### 4.1.2. State reconstructors

The values of system variables, state variables especially, which cannot be directly measured have nevertheless to be determined. Classical means for doing this are for linear systems:

- asymptotic observers,
- Kalman filters,

which have enjoyed an immense popularity. Note however that:

- asymptotic observers are quite sensitive to mismatches and perturbations,
- Kalman filters are necessitating the solution of a Riccati equation, where the precise statistics of the noise has to be quite accurately known. It is moreover well known that the *extended Kalman filters* for nonlinear systems has never received a fully satisfactory justification.

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[12] Some concrete laboratory examples are working well at CINVESTAV, México.

For nonlinear systems the question has remained largely open in spite of a huge literature.

When those quantities are considered as unknown parameters, our previous techniques are applicable. We obtain *state reconstructors* which yield excellent estimates even with non-classic stochastic noises, with poorly known statistics.

Note that, in the case of a finite-time reconstructor, the separation principle holds for a large class of nonlinear systems, *i.e.* control and reconstruction can be achieved separately. This reduces the complexity at the global design level.

Another field of interest in the framework of state reconstruction is the design of so-called "unknown input observers". The objective is to recover the value of the state in spite of the presence of unknown inputs. Some members of the project recently derived an observation algorithm that allows for the relaxation of some structural conditions usually assumed in most of the works related to unknown input observers [17], [16]. Actually, it appears that such a method can be performed for a class of left invertible linear systems under the possibility to design finite time observers (or fast estimators). This method is being extended for a special class of nonlinear systems using differential geometric concepts. It is believed that algebraic methods can be a powerful tool in this area: to derive structural conditions whether the aforementioned algorithm might work or not both for linear [24] and nonlinear systems, to numerically test these conditions and to quickly compute the required variables.

### 4.1.3. Fault diagnosis

For a better understanding of complex industrial processes, fault diagnosis has recently become an important issue, which has been studied under various guises (See, e.g., M. Blanke, M. Kinnaert, J. Lunze, M. Staroswiecki, *Diagnosis and Fault-Tolerant Control*, Springer, 2003). In spite of this, the crucial problem of detecting and isolating a fault in closed loop for a possibly uncertain system remains largely open. Our estimation techniques enabled us to give a clear-cut answer, which is easily implementable.

A fault occurrence can lead to a reduction in performance or loss of important function in the plant. The quite particular problem to consider is the design of a fault-tolerant controller. Indeed, the number of possible faults, drastic change in system behaviour and time of fault occurrence play a crucial role. However, ensuring that the performances of the system remain close to the nominal desired performance after a fault occurrence, represents a challenge, which we are now solving: for instance, we presented an invited paper for the *Festsschrift* of Prof. Dr.-Ing. M. Zeitz which took place in September 2005.

## 4.2. Application to signal, image and video processing

### 4.2.1. General presentation

Three patents are already pending in those topics:

1. compression of audio signals,
2. demodulation and its theoretical background[13],
3. compression, edge and motion detection of image and video signals[14].

It is therefore difficult in this report to give too much details. We will limit ourselves to:

1. an academic example which indicates that our approach is indeed powerful enough for detecting abrupt changes in real time.

This last example as well as the two examples of the note have been borrowed from the famous book by Prof. S. Mallat (*A Wavelet Tour of Signal Processing*, 2nd ed., Academic Press, 1999), where he writes that no convincing treatment has yet been obtained *via* existing theories.

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[13] This should be a US patent since it contains the corresponding mathematical apparatus.

[14] The extension to image and video processing will of course involve linear differential operators with respect to several indeterminates.

### 4.2.2. Detection of abrupt changes

Abrupt changes in a signal generally represent important information-bearing parameters. The presence of such transient phenomena in the electroencephalogram (EEG) records may reveal pathology in the brain activity. In such an instance, the detection and location of the change points may be critical for a correct diagnostic. As a first step towards a more general study of gap detection, we have considered a non-stationary piecewise polynomial signal. With our method, it is possible

- to calculate the coefficients of the various polynomials in the presence of noises which might be non-Gaussian,
- to determine quite precisely the locations of the change points.

As an example, consider the estimation of the sequence

$$\begin{aligned} p_0(t) &= -3(t-t_0)+3, \\ p_1(t) &= -4(t-t_1)^3/6+5(t-t_1)^2/2-2(t-t_1)+2, \\ p_2(t) &= (t-t_2)^2-2(t-t_2)+2 \end{aligned}$$

of unknown time polynomial signals measured by $y_i(t)=p_i(t)+\varpi(t)$ where $\varpi(t)$ is a zero mean value stochastic process constituted, at each time $t$, by a rectangularly distributed computer-generated random variable. Figure 3 shows the sequence of polynomials estimates, which are seen to converge quite fast to the ideal signal and the results of the constant parameter identification in the noisy environment. It should be pointed out that in the previous simulations, the instants $t_i$, at which the polynomial signal $p_i(t)$ changed into a new one $p_{i+1}(t)$, were known beforehand. It is not difficult to see that the proposed identification algorithm is also capable of depicting the instant at which the new polynomial signal arrives, when such discontinuity instants are randomly selected. Being unaware of the signal change, results in a noticeable drifting of the constant values of the parameters being currently identified. This allows for a simple and timely re-initialization of the estimation algorithm. Figure 4 depicts an example of the estimated parameters drift that occurs when a second order polynomial signal is suddenly changed to a different one.

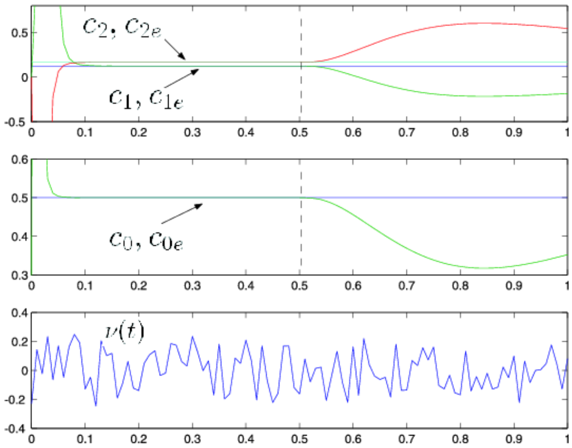

*Figure 3. A sequence of noisy measured polynomial signals, generated by a noisy system, and their estimated parameter values*

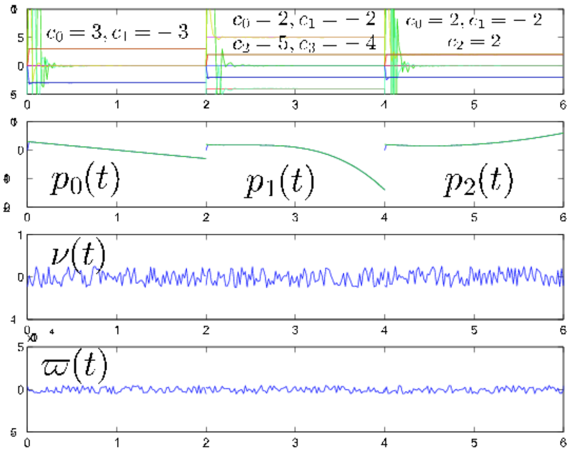

*Figure 4. Identification of a discontinuity time in a perturbed time-polynomial signal parameter identification process.*

# 5. Software

## 5.1. Experimental software

ALIEN aims at developing algorithms, but not commercial softwares. However, we intend to make available part of the programs used in our researchs and publications in order to make easier the diffusion of our ideas.

The Maple package developped by Alexandre Sedoglavic [40] to test observability is available at url: http://www2.lifl.fr/ sedoglav/Software/ObservabilityTest/

# 6. New Results

## 6.1. Introduction

The manifold success of our viewpoint in various branches of mathematical engineering is indicating directions for researches in a near future.

## 6.2. Algorithmic and numerical aspects of estimation

Our calculations are resting on the two following aspects:

- Algebraic elimination of some system variables. Here again the use of non classical data structures forms a keystone for accelarating algebraic computations and eventually producing naturally efficient numerical programs.
- Manipulation of matrices, which are ill-conditioned since the integration time is very short.

Improving our results will therefore necessitate a combination of algorithms stemming from computer algebra and numerical analysis which needs to be better understood.

## 6.3. New concrete examples in control

New concrete examples from various technological fields will be investigated. It is worth noticing that several experimental benchmarks are already available at LAGIS laboratory (mobile robots, stepper motor, cart-pendulum) as well as at ECS laboratory (benchmark on multi-cell chopper).

### *6.3.1. Collaborative robots*

The cooperation between several agents is a challenging trend from both economical and scientific points of view. A large number of applicative fields can be cited: Transportation (unit of mobile robots), Health (remotely-operated surgery robots), Environment or Defence (fleet of drones or UAV), Space (constellation of satellites), Machining (over-actuated systems)... The cooperating devices have to fulfill a common objective, subject to environment perturbations and using a limited number of sensors. Then, it makes sense to use fast reconstruction of state variables as well as of exogenous parameters (force feedback, obstacle positions...). It is aimed at designing computationally efficient algorithms, based on algebraic estimation techniques, and working out the required information on the basis of the available sensors and communication links.

### *6.3.2. Magnetic levitation*

Magnetic levitation systems have received much attention as a way of eliminating Coulomb friction due to mechanical contact. Levitation bearing has been used from the beginning in rotating machinery to support rotors without friction providing low energy consumption, high rotational speed, with no lubrication and greater reliability. It also allows a simpler and safer mechanical design as in the case of pumps used in nuclear installations where fluid leakage avoidance is of primary importance. Magnetic bearings are also becoming increasingly popular in the precision industry, with significant demands on accurate positioning. One can quote nanometric servo-position actuator in micro-lithography industry as well as vibration isolation in precision scientific instruments. High-speed ground transportation systems constitute another application, probably the most famous: Japanese “Maglev” and German “Transrapid” are very fast trains using the principle of a linear motor hanged up over a magnetic rail.

Magnetic levitation systems highlight phenomena like strong nonlinearities, fast dynamics, actuator saturations and uncertain parameters. Many control techniques have been quite successfully implemented on levitation systems. Within the control methodologies, one can cite, for instance, feedback linearization control, flatness based control, passivity based control, or backstepping design approach. However the performances are limited by the model relevance as well as its parameters accuracy. Estimation of these parameters is a motivating problem and it is aimed at developing and testing control laws based on closed-loop identification methods. In the next few months, a magnetic shaft benchmark will be developed in Lille in collaboration with Dr. Joachim Rudolph from the University of Dresden.

### 6.3.3. Friction

Modelling or estimating *on-line* the viscous or dry friction in mechanical systems is a challenging problem with an industrial impact. To mention only the regional framework of “Region Nord - Pas de Calais”, several programs are concerned with brake systems management (ST2 pole[15], *i*-TRANS[16]) as well as friction compensation (ERT CEMODyNE).

By using the fast estimation capabilities, we hope to drastically simplify some difficult modelling problems arising while studying friction. Two benchmarks at LAGIS can be used to illustrate the efficacy of the algebraic methods for the control of electromechanical systems with friction: A linear drive actuating a cart-pendulum, and a stepper motor. Note that the latter is a flat system and so, a linearizing control law based on the fast and robust estimation of the time derivatives of the sensor signals can be considered.

### 6.3.4. Multi-cell chopper

Multi-cell choppers and converters are more and more popular in power electronic, due to three main reasons: (1) The possibility with the same switching component of covering a wide voltage scale. (2) The modularity and flexibility introduced in the design of such choppers or converters. (3) The drastic decreasing of the dv over dt phenomenon.

Unfortunately, due to the complexity of the control (i.e. hybrid system, non universal input...), many of the industrial applications are considered in the vicinity of a given, *static* requested behavior. The algebraic techniques could be considered so to design an observer-based control algorithm valid for more general *dynamic* behaviors. Application domains of such a breakthrough are for instance: Railway traction, Active filter for networks.....

## 6.4. Linear delay systems

Delay estimation may also be a crucial question in concrete situations, since most of the efficient control techniques need the delay as a parameter. Real time identification of delay was considered as an open problem. Scarce results [2], [9] manage an asymptotic identification, the convergence time of which does not guaranty an efficient combination with control or fault diagnosis techniques. The approach introduced in [22] opens a promising track to fast estimation of delays, including the case of variable ones. Several fields of application are concerned.

### 6.4.1. Process engineering

A wide class of plants (chemical engineering, food industry...) can be approached efficiently by a simple linear model with input delay. If it turns out to be possible, the development of a software that provides both the model and the associate controller from industrial data mining (thus, off-line data) is very relevant to industrial concerns.

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[15] Science and Technologies for Safe Transport, the theme 4 of which is devoted to braking mechanics: http://www.polest2.fr .

[16] French *Pôle de compétitivité* on “Railway at the heart of the innovative transport systems”.

### 6.4.2. Aeronautics

Among the various approaches that model the longitudinal flight of an aircraft through a vertical gust, a delay-based description was introduced so to represent the effects of the penetration of the aircraft through the gust. Combining this description with a fast identification algorithm constitutes a track for the aerodynamic coefficients identification. Tests will be carried out at the Flight Analysis laboratory of the DCSD of ONERA in Lille. During those experiments, a model of civil aircraft equipped with an embedded instrumentation will be catapulted and will cross, during a free flight, a turbulence generated by a vertical blower.

### 6.4.3. Networked control

Communication networks (ethernet, wifi, internet, CAN... ) have a huge impact on the flexibility and integration of control systems (remote control, wireless sensors, collaborative systems, embedded systems...). However, a network unavoidably introduces time delays in the control loops, which may put the stability and safety performances at risk. Such delays are varying (jitter) and efficient control techniques (predictor-based) take advantage of their knowledge. Two approaches have to be combined: (1) use delay identification algorithms and improve the control; (2) design control/estimation algorithms that can stand variations of the delay.

## 6.5. Signal, image, and video processing

### 6.5.1. Multi-user detection

In the direct-sequence *code-division multiple access* (DS-CDMA) system, several users share a common propagation channel, by use of spread spectrum signalling. Each user is assigned a unique code sequence corresponding to its *signature*. This signature sequence allows the user to modulate and spread the information-bearing signal across the available frequency band. It is also on the basis of this signature that the receiver distinguishes and separates the corresponding user among the others.

As the different users access the channel asynchronously, the optimum maximum likelihood receiver, which is based on a bench of correlators, has a computational complexity which grows exponentially with the number of users. It seems that our method should lead to a more efficient detection with a reasonable level of complexity.

### 6.5.2. Direction-of-arrival estimation

The problem of estimating the direction-of-arrival of multiple sources incident on a uniform array has received much attention in recent years, especially for wide band sources for which the existing solutions are rather computationally demanding. If $s_k(t)$, $k = 1, \cdots, M$, denotes the $k^{th}$ source signal, the signal $y_i(t)$ received then by the $i^{th}$ sensor, $i = 1, \cdots, N$ is of the form:

$$y_i(t) = \sum_{k=1}^{M} s_i(t - \tau_i(\theta_k)) + n_i(t),$$

where:

- $n_i(t)$ is an additive noise,
- $\tau_i(\theta_k)$ is the (relative) delay of a signal from direction $\theta_k$.

The problem of estimating the direction-of-arrival is equivalent to the estimation of those delays. When a model for the source signal is known[17], this problem admits in our approach a simple and straightforward real-time solution. In a blind situation, where no signal model is available, our method yields good estimates provided the real-time constraint is relaxed.

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[17] This is the case, for instance, in radar and sonar applications.

### 6.5.3. Turbo-codes

The famous discovery of *turbo-codes* by Prof. C. Berrou and the late Prof. A. Glavieux has certainly been the main achievement in the 90s of the theory of error control codes. Besides completely changing not only the theory but also the practical implications of this field, it has given birth to various extensions in signal processing such as *turbo-equalisation*. It seems that turbo-decoding might benefit from our new understanding of estimation.

### 6.5.4. Watermarking

*Watermarking*, which is becoming a hot topic, may be viewed as a type of cryptography where a hidden message has to be inserted in an image or a video. Our approach to image and video processing, which unfortunately could not be reviewed in this report for legal reasons[18], has already given promising preliminary results in this field.

### 6.5.5. Cryptography

After Pecora and Carroll (1991) successfully synchronized two identical chaotic systems with different initial conditions, chaos synchronization has been intensively studied in various fields and in particular in secure communications (because chaotic systems are extremely sensitive to their initial conditions and parameters). The idea is to use the output a particular dynamical (chaotic) system to drive the response of an identical system so that they oscillate in a synchronized manner. An interesting application in secure communication uses such a chaotic master dynamics to mask a message and a synchronized slave system to recover the message.

Since the work of Nijmeijer and Mareels (1997), the chaotic system synchronization problem has been intimately related to the design of a nonlinear state observer for the chaotic encoding system. Many techniques issued from observation theory have been applied to the problem of synchronization, where the receiving system asymptotically tracks the states of the transmitting system: observers with linearizable dynamics, adaptive or sliding mode observers, generalized hamiltonian form based observers, etc.

The key issue here is to take an algebraic viewpoint for the state estimation problem associated with the chaotic encryption-decoding problem and to emphasize its use for the efficient and fast computation of accurate approximations to the successive time derivatives of the transmitted observable output signal received at the decoding end. Those methods should also be useful in new encryption algorithms that require fast estimation of the state variables and the masked message.

*Remark 1* Note that the technological aspects of this new kind of cryptography has nothing to do with number-theoretic cryptography which has become very popular in computer sciences.

### 6.5.6. Comparison with other methodologies

People of the project who belong to LAGIS, as well as Jean-Pierre Barbot, have been working for many years on other methods for fast estimation (of state variables or unknown parameters). Those techniques, that have been widely developed during the last decade in the literature, are often referred as “finite time” observers or estimators: The knowledge of the variables or the parameters is theoretically recovered after a finite time and not asymptotically (as it is usually the case). This approach involves notions such as homogeneous functions or discontinuous functions (one can refer to higher order sliding mode theory or the larger area of variable structure systems). Thus, for several fields of applications, the members of the project have the required background to perform comparisons of variable structure techniques and algebraic methods in the framework of fast estimation and identification.

# 7. Contracts and Grants with Industry

## 7.1. DGA

### 7.1.1. DGA

Michel Fliess has obtained a DGA contract of 25 Keur on signal processing.

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[18] See Section 4.2.1.

# 8. Other Grants and Activities

## 8.1. Regional grants

### *8.1.1. Projet Thématique : Automatique et Systèmes Homme-Machine : applications aux transports*

Thematic research on Automatic control and Man - Machine systems with Application to Transport. Grant in the framework of the program “TAT Technologies Avancées pour les Transports” (Advanced Technologies for Transport) Regional Council of Nord Pas de Calais, French Ministery of Research, European Community (FEDER)

J.-P. RICHARD (manager)

This program joints a fundamental research with applications to transport systems. This includes works devoted to observation of nonlinear systems and delay systems, as well as their application to vehicle control. The global allocated ceiling is 1894 kEuros (including a 1497 kEuros subvention from Region+FEDER) for the GRAISyHM teams (GRAISyHM is a Federation of Automatic control labs in North France). Within this global ceiling, 46.4 kEuros (36.9 kEuros subvention) are concerning J.P. Richard’s team.

### *8.1.2. Robocoop*

“Robocoop : cooperative strategies within tele-operated formations”.

This Arcir ("Actions de recherches concertées d’initiative régionale") has a global funding of 142 200 Eurs (the region Nord Pas-de-Calais is supporting 71 100 Eurs, the remaining being suported by the feder).

This project aims at developing technics belonging to the research field of automatic control that should take into account co-operation and delays due to communications between the robots. The obtained results will be demonstrated on two test benches: one composed of mobile robots and the other one of two manipulators.

### *8.1.3. TAT 3.1 TRACTECO (AS 2005-2007)*

“Action Spécifique TRACTECO : Méthodes de commande, d’observation et d’identification de systèmes non linéaires avec application aux paliers magnétiques” Applied research on Control, observation and identification of nonlineaur systems with application to magnetic bearings.

Grant of 45 Keuros in the framework of the program “TAT Technologies Avancées pour les Transports” (Advanced Technologies for Transport) Regional Council of Nord Pas de Calais, French Ministery of Research, European Community (FEDER)

T. FLOQUET (manager)

The main objective of this program is the design of fast estimation algebraic methods for the control of magnetic bearings. The resulting control laws will be experimentally tested on a benchmark developed in collaboration with J. Rudolph from the University of Dresden, Germany.

## 8.2. National grants

### *8.2.1. Algebraic methods for real-time estimation*

- The case of adherence coefficients for tyre efforts

Grant supported by GdR CNRS 717 MACS “Modélisation, Analyse et Commande des Systèmes dynamiques” (Modelling, Analysis and Control of dynamic Systems). Category “Exploratory research on interdisciplinary joint research”.

H. MOUNIER (manager), Institut d’Electronique Fondamentale, CNRS and University of Paris 11, 8 kEuros

## 8.3. International activities

### 8.3.1. Brasil

**Participant:** Mamadou Mboup.

**DSPCom** Collaboration with the Laboratory of signal processing for communication (DSPCom) of the Faculty of Electrical Engineering and Computer Science (FEEC) of UNICAMP (University of Campinas - Brasil). This collaboration includes Prof. Joao Marcos Romano (head of the laboratory) and Aline Neves who defended her PhD in 2005 with M. Mboup (see [39]).

**UPM** There is another collaboration with the team of research in numerical communication of Universidade Presbiteriana Mackenzie (UPM), Brasil, involving Maria Miranda who came for two weeks in 2006.

Mamadou Mboup has been invited for two weeks at Unicamp in april 2006.

### 8.3.2. Tunisia

**Participants:** Mamadou Mboup, Michel Fliess, Cédric Join.

In september 2005, we made a proposal for a STIC-INRIA project with Tunisia (Modeling and system identification). This project has been renewed in 2006.

# 9. Dissemination

## 9.1. Collective events

### 9.1.1. Summer school Fast estimation and identification methods in control and signal

This summer school was devoted to the new fast methods developped by Alien.

Scientific coordinator : Michel Fliess, Main speakers : Michel Fliess; Cédric Join; John masse, Société APPEDGE; Mamadou Mboup; Johann Reger, University of the Army, Munich; Joachim Rudolph, Technical University, Dresde; Kurt Schlacher, Johannes Kepler University, Linz; Hebertt Sira-Ramirez, CINVESTAV-IPN, Mexico City; Alina VODA, Université Joseph Fourier, Grenoble.

### 9.1.2. ICASSP

During 2006 IEEE International Conference on Accoustics, Speech and Signal Processing, may 14–19 2006, Toulouse, France, the tutorial lecture: “Towards new estimation techniques: Reconciling signal processing and control” was presented by Michel Fliess and Mamadou Mboup. [28]

### 9.1.3. Digital control of industrial processes

During the school “Digital control of industrial processes”, Douz, Tunisia, 5–8 November 2006, lectures were given by Alien members:

“Une introduction aux particularités et généralités des systèmes à retards”, J.-P. RICHARD;

“Systèmes à retards : Identifiabilité et Identification”, L. BELKOURA;

### 9.1.4. Delay Systems workshop

During the Seminar of the “Identification” workshop of CNRS GDR MACS, ENSAM Paris, 17 November 2005, the following lectures were given:

“Identification des paramètres et retards des systèmes linéaires”, L. BELKOURA and J.-P. RICHARD;

“Identification de systèmes à entrées retardées”, L. BELKOURA, J.-P. RICHARD;

### 9.1.5. Seminar of the NECS project

During the seminar of the NECS project “Networked Controlled Systems”, LAG, Grenoble, 27 September 2005 (NECS is now an INRIA project), the following lecture was given:

"Rudiments on Delay Systems and their relation with networked control", J.-P. RICHARD.

### 9.1.6. Seminar of the CNRS Research Group GdR ARP

Seminar "Networked Control Systems" of the CNRS Research Group GdR ARP, theme Real-Time Systems - QoS, Paris, 17 June 2005, the following lecture was given:

"Systèmes à retards : une introduction à l'usage des non-automaticiens", J.-P. RICHARD.

## 9.2. Teaching

### 9.2.1. Multi-partner Marie Curie Control Training Site

The Multi-partner Marie Curie Training Site, entitled Control Training Site is funded by the European Commission with a global support over four years (Starting January, 2002) of 960 fellow-months. The lead organization is the CNRS at Gif-sur-Yvette, France.

This site organizes international doctoral studies in the scientific area of control theory, optimization and applications. The CTS is addressed to any European student starting the doctoral studies or pursuing doctoral studies in the large domain of Control and Optimization, including various domains of control theory, optimization and control engineering.

Michel Fliess has given 12 hours lectures on Alien's estimation methods.

### 9.2.2. École polytechnique of Tunis

Michel fliess has given 25 hours lectures at École polytechnique of Tunis in 2006.

### 9.2.3. MPRI

**Participant:** François Ollivier.

François Ollivier has given level 2 lectures in the course "Algorithms in Computer Algebra and Control" of the Parisian Master of Research in Computer Science (MPRI).

# 10. Bibliography

## Major publications by the team in recent years

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