INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team alien

ALgèbre pour Identification et Estimation Numériques

Futurs

THEME COM

Activity Report

2005

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1. Team

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2. Overall Objectives

2.1. Overall Objectives

ALIEN is located at the Laboratoire d'Informatique de l'École polytechnique (LIX).

The aim of the ALIEN project is to promote new algebraic techniques for estimation and identification, especially in automatic control and in signal processing.

It is clear from this sentence that we combine high-level mathematics and quite concrete applications. The tools we are employing stem mainly from differential algebra, module theory, and operational calculus, which yield most efficient interpretations of estimation and identification questions. Whenever possible, we produce at least computer simulations related to well-known case-studies for validating our approach.

Our main areas of expertise comprise:

- **Linear control systems**. Our real-time algorithms permit perhaps for the fist time to achieve closed-loop parametric identification, *i.e.*, we are able to identify and control simultaneously a given plant.
- **Demodulation**. Fast and efficient demodulation techniques for communication purposes via parametric estimation in a noisy environment.
- **Transient signals**. Analysis, compression and detection of abrupt changes for noisy transient signals via efficient procedures for estimating their derivatives.
- **Nonlinear control systems**. By considering the input and output signals as noisy transient signals, we are able to propose real-time state and parametric estimators.
- **Fault diagnosis and accommodation**. Fault diagnosis and accommodation for linear and nonlinear systems by translating the main questions of these topics in our language of algebraic estimation theory.
- **Image and video processing**. Extension to several dimensions of our techniques for transient signals.

3. Scientific Foundations

3.1. General description

Keywords: *closed-loop state variables and parameter estimation*, *compression*, *demodulation*, *edge and motion detection*, *equalization - compression*, *image and video processing*, *linear and nonlinear control*, *on-line diagnosis*, *real-time identification*, *signal processing*.

identification moyen informatique permettant d'obtenir des valeurs numériques, décrivant les paramètres d'un système physique, conformément à un modèle donné.

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 Θ of parameters,
- n is a noise corrupting the observation.

Finding a "good" approximation of the components of Θ 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[1] 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 a most classical tool among control and mechanical engineers[2].

Let us briefly mention some chapters 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,
- estimation of state variables, which are not measured,
- fault diagnosis and isolation.

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.

[1]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.

[2]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 not the Fourier transform over $\mathbf{R}$.

3.2. Identifiability

Parameter identification is a key step in modeling. 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 behavior 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 behavior of the system.

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

$$P\begin{pmatrix}\theta_1\\ \vdots\\ \theta_r\end{pmatrix} = Q \tag{2}$$

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 ξ 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 (2) becomes

$$P\begin{pmatrix}\theta_1\\ \vdots\\ \theta_r\end{pmatrix} = Q + R \tag{3}$$

where R is a column $r\times 1$ 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 η is a perturbation or a noise.

3.2.3. Structured perturbations

A perturbation π 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 (3) by a suitable differential operator Δ such that equation (3) becomes

$$\Delta P\begin{pmatrix}\theta_1\\ \vdots\\ \theta_r\end{pmatrix} = \Delta Q + R' \tag{4}$$

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

3.2.4. 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.

3.2.5. Comments

Although the previous noise attenuation[3] may be fully explained via formula (4), its theoretical comparison[4] with today's literature[5] 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.

3.3. Some hints on the calculations

The time derivatives of the input and output signals appearing in equations (2), (3), (4) 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 (4) during a very short time interval.

3.4. 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 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.

4. New Results

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 when 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[6].

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.

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.

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

[4] 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.

[5] Especially in signal processing.

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

4.1.3. Fault diagnosis

For better understanding complex industrial processes, fault diagnosis has recently become a most 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, to ensure, after fault occurrence, that the performances close to the nominal desired performance represents a challenge, which we are now solving: we are for instance preparing an invited paper for the *Festsschrift* of Prof. Dr.-Ing. M. Zeitz which will take place in September 2005.

4.2. Applications 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[7],
3. compression, edge and motion detection of image and video signals.

It is therefore difficult in this report to give too much details. Let us just mention that several of our existing publications give an efficient and simple solutions for various concrete case-studies (analysis and compression of transient signals, detection of abrupt changes), borrowed for instance from the famous book due to 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.

5. Other Grants and Activities

5.1. National initiatives

5.1.1. AS Algebraic methods for numerical communication systems

Participants: Mamadou Mboup, Michel Fliess.

Action Spécifique-191 : "Algebraic methods for numerical communication systems", in the framework of Réseau Thématique Plurisciplinaire RTP-24, “Mathematics of systems and signals”.

5.2. European initiatives

5.2.1. IFATIS

Participant: Cédric Join.

IFATIS (Intelligent Fault Tolerant Control in Integrated systems), duration of project: 01/01/2002 - 31/03/2005.

http://ifatis.uni-duisburg.de/

5.2.2. NeCST

Participant: Cédric Join.

NeCST (Networked Control Systems Tolerant to faults), in progress.

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

http://www.strep-necst.org/

5.3. International initiatives

5.3.1. 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 l'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 [7]).

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 one month in 2005.

5.3.2. Tunisia

Participants: Mamadou Mboup, Michel Fliess.

In september 2005, we made a proposal for a STIC-INRIA project with Tunisia (Modeling and system identification).

5.3.3. Morroco

Participants: Saïd Moutaouakil, François Ollivier.

We have a long term collaboration with Prof. Brahim Sadik (former student of F. Ollivier) at Faculty of Sciences Semlalia, University Cadi Ayyad, Marrakech. Saïd Moutaouakil is a co-tutelle PhD student in Ecole polytechnique and University Cadi Ayyad, Marrakech

5.4. Visiting Scientists

M. Fliess has been invited twice in Germany for a week (Mathematisches Institut Oberwolfach, Universität des Bunderwehr Munich).

Mamadou Mboup has been invited once in Germany for a week (Universität des Bunderwehr).

François Ollivier has been invited for ten days a university Cadi Ayyad in Marrakech in june 2005.

J. Reger (Universitaet der Bundeswehr, Munich) and H. Sira-Ramirez (CINVESTAV, Mexico City, Mexico) have been invited for two weeks in Paris in jully 2005.

6. Dissemination

6.1. Involvment with the scientific community

Besides the usual editorial activities in various scientific journals and conferences, the team has organized, with the help of the CNRS and INRIA Futurs a summer school in Paris (Fast Estimation Methods in Automatic Control and Signal Processing) on the estimation techniques. This school was well attended and many foreigners took part.

Another German summer school took place on more or less the same topics at the Bundeswehr Universität München, Munich, Germany, where our team played a prominent role (Identification, Sate Reconstruction, and Generalized PI-Control).

F. Ollivier has given a talk about Maxima and the free software for symbolic computation, during the "Journée technique : Les Applications Scientifiques et Industrielles des Logiciels Libres" in may 2005.

6.2. Teaching

6.2.1. 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).

7. Bibliography

Major publications by the team in recent years

[1] M. FLIESS, C. JOIN, M. MBOUP, H. SIRA-RAMÍREZ. *Compression différentielle de transitoires bruités*, in "C.R. Acad. Sci. Paris, Ser. I", vol. 339, 2004, p. 821-826, http://www.stix.polytechnique.fr/publications/fliess/compression.pdf.

[2] M. FLIESS, C. JOIN, H. SIRA-RAMÍREZ. *Robust residual generation for linear fault diagnosis: an algebraic setting with examples*, in "Internat. J. Control", vol. 77, 2004, p. 1223-1242, http://www.stix.polytechnique.fr/publications/fliess/panne-art-postreview.pdf.

[3] M. FLIESS, R. MARQUEZ, E. DELALEAU, H. SIRA-RAMÍREZ. *Correcteurs proportionnels intégraux généralisés*, in "ESAIM Control Optim. Calc. Variat.", vol. 7, 2002, p. 23-41, http://www.edpsciences.org/articles/cocv/abs/2002/01/cocvVol7-2/cocvVol7-2.html.

[4] M. FLIESS, H. SIRA-RAMÍREZ. *An algebraic framework for linear Identification*, in "ESAIM Control Optim. Calc. Variat.", vol. 9, 2003, p. 151-168, http://www.stix.polytechnique.fr/publications/fliess/sira6.pdf.

[5] M. FLIESS, H. SIRA-RAMÍREZ. *Control via state estimations of some nonlinear systems*, in "Proc. NOLCOS", 2004, http://www.stix.polytechnique.fr/publications/fliess/NLIO1.ps.

[6] M. FLIESS, H. SIRA-RAMÍREZ. *Reconstructeurs d'états*, in "C.R. Acad. Sci. Paris, série I", vol. 338, 2004, p. 91-96, http://www.stix.polytechnique.fr/publications/fliess/observateurs.pdf.

Doctoral dissertations and Habilitation theses

[7] A. NEVES. *Identification algébrique et déterministe de signaux et systèmes à temps continu: application à des problèmes de communication numérique*, Ph. D. Thesis, Université Paris V, 2005.

Articles in refereed journals and book chapters

[8] M. FLIESS, C. JOIN, H. MOUNIER. *An introduction to nonlinear fault diagnosis with an application to a congested internet router*, in "Advances in Communication Control Networks", vol. 338, 2005, p. 327-343, http://www.stix.polytechnique.fr/publications/fliess/final_C.ps.

Publications in Conferences and Workshops

[9] M. FLIESS, C. JOIN, M. MBOUP, A. SEDOGLAVIC. *Estimation des dérivées d'un signal multi-dimensionnel avec applications aux images et aux vidéos*, in "Actes 20e coll. GRETSI", 2005, http://www.stix.polytechnique.fr/publications/fliess/gretsi.pdf.

[10] M. FLIESS, C. JOIN, M. MBOUP, H. SIRA-RAMÍREZ. *Analyse et représentation de signaux transitoires : application a la compression, au débruitage et à la détection de ruptures*, in "Actes 20e coll. GRETSI", 2005, http://www.stix.polytechnique.fr/publications/fliess/gretsi05.pdf.

[11] M. FLIESS, M. MBOUP, A. NEVES, H. SIRA-RAMÍREZ. *Une autre vision de l'identification de signaux et systèmes*, in "Actes Conf. Internat. Franc. Automatique (CIFA)", 2004.

[12] C. JOIN, M. FLIESS, H. SIRA-RAMÍREZ. *Fault diagnosis of closed loop linear systems with parametric uncertainties*, in "Proc. DX'04 (15th Internat. Workshop Principles Diagnosis)", 2004, p. 111-116., http://www.stix.polytechnique.fr/publications/fliess/paper_final_V4.pdf.

[13] C. JOIN, H. SIRA-RAMÍREZ, M. FLIESS. *Control of an uncertain three-tank-system via on-line parameter identification and fault detection*, in "IFAC World Congress on Automatic Control", IFAC, 2005, http://www.stix.polytechnique.fr/publications/fliess/WIFAC05_12.pdf.

[14] A. NEVES, M. MBOUP, M. FLIESS. *An algebraic identification method for the demodulation of QPSK signal through a convolutive channel*, in "EUSIPCO'04", 2004, http://www.stix.polytechnique.fr/publications/fliess/eusipco04final.pdf.

[15] J. REGER, H. SIRA-RAMÍREZ, M. FLIESS. *On non-asymptotic observation of nonlinear systems*, in "Proc. CDC-ECC'05", 2005, http://www.stix.polytechnique.fr/publications/fliess/cdc_after_review.pdf.

[16] H. SIRA-RAMÍREZ, M. FLIESS. *On the output feedback control of a synchronous generator*, in "Proc. 43rd IEEE Conf. Decision Control", 2004, http://www.stix.polytechnique.fr/publications/fliess/PAPER2.PDF.