INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team Sosso

Applications and tools for automatic control

Rocquencourt

THEME 4A

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2. Overall Objectives

The goal of this project is to develop and promote methods for automatic control, in particular for modelling and analysis of complex controlled systems. The main application fields are Health, with diagnosis in cardiology and ovulation control, and Automobile, with low-emission vehicles. The project is being reorganized: a new project is in preparation, based on the following present themes.

Research themes
Mathematical modelling, identification and control of:

- Nonlinear systems with hysteresis or delays. Applications include control of friction-intensive mechanical systems and cardiac mechanics.

- Reaction-diffusion systems with applications in automobile-emission reduction and cardiac electrophysiology.
- Hybrid dynamical systems with applications in Automobile (transmission systems) and Health (genetic regulatory networks).
- Multiscale dynamical systems with applications in cardiac mechanics and ovulation control.
- Model-based signal processing with applications in cardiological diagnosis.

5. Software

5.1. Software

Participant: Claire Médigue.

5.1.1. LARY_CR: Software package for the Analysis of Cardio Vascular and Respiratory Rhythms, in the SCILAB_SCICOS environment

LARY_CR is a software package dedicated to the study of cardiovascular and respiratory rhythms, developed in the SCILAB_SCICOS scientific environment [73]. It presents signal processing methods, from events detection on raw signals to the variability analysis of the resulting time series. The events detection concerns the heart beat recognition on the electrocardiogram, defining the RR time series, the maxima and minima on the arterial blood pressure defining the systolic and diastolic time series. These detections are followed by the resampling of the time series then their analyse. This analyse uses temporal and time frequency methods: Fourier Transform, spectral gain between the cardiac and blood pressure series, Smooth Pseudo Wigner_Ville Distribution, Complex DeModulation, temporal method of the cardiovascular Sequences. The objective of this software is to provide some tools for studying the autonomic nervous system, acting in particular in the baroreflex loop; its functionning is reflected by the cardiovascular variabilities and their relationships with the other physiological signals, especially the respiratory activity.

6. New Results

6.1. Control theory

6.1.1. Linear Matrix Inequalities and Control of Parameter-Dependent Systems

Participant: Pierre-Alexandre Bliman.

Key words: *hybrid systems*, *stability*, *LMI*.

We pursued this year the study of the methods previously developed.

First, we proved a result on existence of polynomial solutions for LMIs depending continuously upon scalar parameters lying in a compact set. This result generalizes some partial results of the same type, which were based on analyticity.

Moreover, this offers e.g. a general framework to study systems stabilization by gain-scheduling, by nonconservative methods. Indeed, state-feedback stabilization of usual may be solved by a standard LMI. Consequently, the issue of state-feedback stabilization for parameter-dependent systems amounts to solve a parameter-dependent LMI. By use of the preceding result, no loss of generality is introduced if assuming that the solution of the latter is polynomial. As a consequence, we proved that, when the system depend polynomially upon the parameters, a countable family of LMIs of increasing precision may be constructed (indexed by the degree of the polynomial parameter-dependent solution), and whose solution provides parameter-dependent stabilizing gain.

6.1.2. Stability and stabilizability of nonlinear delay systems

Participants: Pierre-Alexandre Bliman, Frédéric Mazenc (Projet Conge, INRIA Lorraine).

Backstepping is one of the most popular synthesis techniques for the nonlinear systems. Among its many advantages, it provides large family of globally asymptotically stabilizing control laws, permits to ensure a certain amount of robustness to the control and to solve adaptative problems.

We began the generalization of this technique to delay systems. As an example, we look for stabilizing feedback fot the system

$$\dot{x} = xz, \quad \dot{z} = u(t-h) \quad ,$$

which has the particularity of not being locally exponentially stabilizable.

6.1.3. Robust control of delay systems

Participants: Catherine Bonnet, Jonathan Partington [Leeds University].

We have considered this year the H_∞ and BIBO stabilization of delay systems of neutral type with transfer function of the form

$$G(s) = \frac{r(s)}{p(s) + q(s)e^{-sh}},$$

where $h > 0$, and p, q and r are real polynomials. The condition that the system be of neutral type implies that $\deg p = \deg q$. Also, it is necessary for stability that $\deg r \leq \deg p$, so that we have made this assumption as well. Our analysis would apply unchanged to transfer functions $G(s)e^{-sT}$ for $T > 0$ [42].

As is well-known, such systems possess poles which lie in a band centred on the imaginary axis and are more delicate to analyse than retarded delay systems which possess only finitely many poles in the right half-plane.

Here it has been possible to analyse precisely the asymptotic location of the poles of G (asymptotic to a vertical line in the left half-plane, to a vertical line in the right half-plane or to the imaginary axis) considering the value of $\alpha = \lim_{|s|\to\infty} p(s)/q(s)$. Some H_∞ or BIBO stability conditions were then derived in terms of α and the degrees of p, q and r.

Those results were then applied to discuss the stabilizability of such systems by finite-dimensional controllers or controllers possessing a coprime factorization over $L^1 + \mathbf{C}\delta$ or $A(\mathbf{C}_+)$ (the space of functions that are continuous on the closed right half-plane and analytic on the open half-plane $\mathbf{C}_+$, possessing a unique limit at $\pm i\infty$).

We are now considering the use of these stability conditions of neutral systems to evaluate the stabilizing properties of a PID for a dead-time system $e^{-sT}R(s)$, where $T > 0$ and R is a rational function.

Another project running in this area is the robust stabilization of systems with multiple transmission delays.

6.1.4. Single-linkage clustering for piecewise affine regression

Participant: Giancarlo Ferrari Trecate.

This research focuses on data-based modelling of hybrid systems. More specifically, we consider the problem of reconstructing Piece-Wise Affine (PWA) systems from a finite number of noisy data.

A PWA functions is defined by the equations

$$\begin{array}{rcl} f(x) & = & f_q(k) \quad \text{if} \quad x \in \overline{\mathcal{X}}_q \\ f_q(x) & = & \left[\begin{array}{cc} x^T & 1 \end{array} \right] \overline{\theta}_q \end{array} \tag{1}$$

where $\mathbb{X} \subset \mathbb{R}^n$ is a bounded polyhedron, $\{\overline{\mathcal{X}}_q\}_{q=1}^s$ is a polyhedral partition of $\mathbb{X}$ in s regions and $\overline{\theta}_q \in \mathbb{R}^{n+1}$ are parameter vectors. In other words, a PWA function is composed by s *modes* defined by the pairs $(\overline{\theta}_q, \overline{\mathcal{X}}_q)$. The available data are the pairs $(x(k), y(k))$, $k = 1, ..., N$ generated by the model

$$y(k) = f(x(k)) + \eta(k) \tag{2}$$

where $\eta(k)$ is the measurement noise. The aim of a PWA regression algorithm is to provide the mode estimates $(\theta_q, \mathcal{X}_q)$, $q = 1, ..., s$ by using the collected data. In the context of hybrid systems, an input/output description of PWA systems [76] with inputs $u(k) \in \mathbb{R}^m$ and outputs $y(k) \in \mathbb{R}$ is provided by the model (2) where k is now the discrete-time index and $x(k)$ is defined as

$$x(k) = \left[\begin{array}{cccccc} y(k-1) & ... & y(k-n_a) & u^T(k-1) & ... & u^T(k-n_b) \end{array} \right]^T. \quad (3)$$

Note that, for n_a and n_b given, the identification problem is recast into a PWA regression problem.

The main difficulty of PWA regression, with respect to standard linear regression, is that the data points must be *classified*, i.e. attributed to the mode that generated them. Since mode regions are unknown, this task cannot be decoupled from the problem of estimating the model parameters. An efficient algorithm for solving PWA regression problems has been proposed in [71][70]. This procedure exploits the joint use of linear identification, clustering and pattern recognition algorithms. In particular, the classification problem is recast into a clustering problem that can be numerically solved via a suitable K-means-like technique.

The main drawback of supervised clustering algorithms, like K-means, is that the number of clusters to be found must be specified *a priori*. In PWA regression, this is equivalent to knowing the number s of modes composing the overall systems. When this information is not available, the number of modes itself must be automatically found. In order to achieve this goal we investigated the use of single-linkage clustering that is capable to find automatically the proper number of clusters. In particular, we proved that single-linkage clustering, coupled with a suitable rule for accepting or rejecting the clusters found, can guarantee optimal classification if the noise level is small enough. Single-linkage algorithms requires the specification of a threshold whose choice may be critical. We studied this point by showing theoretically and through a benchmark problem that in the "small-noise" case, the optimality of the algorithm is robust against threshold mis-specifications.

6.1.5. Data-Based Hybrid modelling of the Component Placement Process in Pick-and-Place Machines

Participant: Giancarlo Ferrari Trecate.

We conducted an experimental study in the identification of the electronic component placement process in pick-and-place machines. Pick-and-place machines are used to automatically place electronic components on printed circuit boards (PCBs), and form a key part of an automated PCB assembly line. A pick-and-place machine works as follows: the PCB is placed in the working area of the mounting head; the mounting head, carrying an electronic component (using, for instance, a vacuum pipette), is navigated to the position where the component should be placed on the PCB; the component is placed, released, and the process is repeated with the next component

We focus our attention on the subtask of the component placement on the PCB. Assuming that the mounting head, carrying the component, is in the right position above the PCB, the component is pushed down until it comes in contact with the PCB and then released. The PCB is not rigid, but, depending on the material, has certain elasticity properties. In order to study the placement process, an experimental setup was made at the TU Heindoven. It consists of the mounting head, from an actual pick-and-place machine, which is fixed above an impacting surface in contact with the ground via a spring. The chosen design of the impacting surface simulates the elasticity properties of the PCB as well as hard mechanical constraints due to saturations. It also account for realistic linear and dry friction phenomena.

Saturations, impacts and dry frictions introduce hybrid dynamics and the hybrid systems identification algorithm, discussed in section 6.1.4, has been applied.

The results demonstrate that the PWARX models are flexible enough to describe the dynamics of the experimental setup. Despite the fact that the models are optimized for one-step-ahead prediction their

performance in simulation is satisfactory, which makes them adequate for computer simulation, model-based control synthesis, and verification. Physical insights about the experimental setup allow also to isolate specific model features that are not well reconstructed. This information may be used to design the targeted identification experiments where unsatisfactory modes are better excited in order to refine the results.

6.1.6. Computation Observability Regions for Discrete-time Hybrid Systems

Participants: Giancarlo Ferrari Trecate, Mehdi Gati.

The interest in hybrid systems goes beyond their use for simulation. In fact, each class of hybrid models provides a mathematical framework for addressing analysis and synthesis problems. Concerning analysis, a large stream of research focused on the development of methods for verifying structural properties such as stability, controllability and observability A fairly complete study of observability for Mixed Logic Dynamical (MLD) systems is reported in [3] and it is instrumental to the design of moving-horizon state observers enjoying convergence properties [16]. In particular, by proving the equivalence between MLD and piecewise affine systems, the authors show, through counterexamples, three important facts. First, observability over an infinite time horizon is undecidable. Therefore, for a general MLD system, one should resort to a notion of observability in finite time. Second, the observability/unobservability of the overall systems cannot be deduced from the observability/unobservability of the affine modes. Third, the set of states that are observable may be non convex and disconnected. Despite these difficulties, numerical tests based on mixed-integer linear programming have been proposed in order to check if a subset of the state space is observable [3].

The main drawback of these algorithms is that the region to be tested must be specified *a priori*. Therefore, if it contains a large set of observable states and a small set of unobservable states such tests give a negative answer without revealing the presence of the observable subregion. This problem is critical in view of the fact that the computational cost of trial-and-error procedures for finding observable regions is usually prohibitive.

We focus on the automatic computation of the maximal observability region (i.e. the maximal set of observable states) for an MLD systems. The rationale underlying our procedure can be summarized in the following steps. First, we show that the set of states indistinguishable from a given state x can be represented through linear mixed-integer inequalities parametrized by x. Moreover, the computation of the state x', indistinguishable from x and maximizing $\|x - x'\|_1$, can be recast into a multi-parametric Mixed Integer Linear Programming (mp-MILP) problem with parameter x. Basic results of mp-MILP theory show that the map $\Gamma(x) = x'$ is piecewise affine and mp-MILP solvers allow to computed it in closed-form [69], [68]. Finally, the maximal observability region is found as the set of fixed points of Γ. Quite remarkably, the piecewise affine structure of Γ implies that the maximal observability region is the union of finitely many polytopic sets $\mathcal{C}_j$ that can be found by applying the proposed algorithm.

6.2. Modelling, control and biosciences: multi-scale models of the controlled cadiovascular system

The function of the circulation is to supply tissues with oxygen, nutrients and to remove carbon dioxide and other catabolits. Variables involved in cardiovascular regulation, such as blood flow, blood pressure level, oxygen blood concentration, are kept around their reference point by several feedback control mechanisms. These control mechanisms have different dynamics and we are interested only in the short term control of blood flow and pressure which is assumed by the autonomic nervous system through baroreceptor control loops. The aim of this research is to relate classical discrete-time cardiovascular signal analysis to models of the cardiovascular and control systems taking into account its multiple feedback loop organisation. Cardiovascular modelling leads us to the definition of several discrete-time feedback loop sensitivities of pratical interest and to an approach for the estimation of the classical blood-pressure/heart-beating-period baroreflex sensitivity.
Models of the electro-mechanical activity of the cardiac muscle are very useful at the scale of the cardiovascular system as well as at the organ scale. In this later case, they are used for computing stress, strain and action potential fields from three-dimensional image processing. We present a chemically-controlled constitutive law of cardiac myofibre mechanics devoted to be embedded into macroscopic models. This law ensues from the

modelling of the collective behaviour of actin-myosin molecular motors converting chemical into mechanical energy. The resulting dynamics of sarcomeres is consistent with the "sliding filament hypothesis" of A. F. Huxley.

6.2.1. Multi-scale modelling of the controlled contraction of cardiac muscle

Participants: Frédérique Clément, Michel Sorine.

This work has been undertaken within the framework of the ARC ICEMA-2.
http://www-rocq.inria.fr/sosso/icema2/icema2.html

We use ideas originating from the kinetic equation theory to model, on the molecular scale, the controlled collective behaviour of actin-myosin nanomotors at the root of muscle contraction. The classical Huxley's model is recovered on the sarcomere scale by using moment equations. A controlled constitutive law on the tissue scale is obtained using the same type of scaling techniques. This multi-scale description of controlled muscle contraction may be useful in studying modelling and control problems associated to the heart considered as a multi-scaled system. The control viewpoint is useful in accounting for macroscopic properties (such as the Starling law or the Hill force-velocity relation) on lower scales and defining performance indexes of the electro-mechanical coupling on each scale.

6.2.2. The cardiovascular system and its short-term control: modelling and signal analysis

Participants: Frédérique Clément, Emmanuelle Crépeau-Jaisson, Giancarlo Ferrari Trecate, Claire Médigue, Yves Papelier, Michel Sorine, Panagiotis Tsiotras.

This work has been undertaken within the framework of the ACI SCARAMOCO.
http://www-rocq.inria.fr/sosso/ACI/scaramoco.html

The function of the circulation is to supply tissues with oxygen, nutrients and to remove carbon dioxide and other catabolits. The organs involved in this function are: the lungs which allow gas exchanges, the heart which pumps blood and the vascular system which carries molecules to the tissues, see fig. (1).

The regulation of these exchanges is under *hemodynamic* mechanisms, which tend to keep physiological variables around a control level; these mechanisms have to adapt the cardiovascular system to changes (orthostatisme as well as exercise). A strict *homeostasis* point of view reduces the complexity of the living systems regulation. Variables involved in cardiovascular regulation, such as blood flow, blood pressure level, oxygen blood concentration, are kept around their reference point by feedback control mechanisms.

These control mechanisms have different dynamics and we are interested only in the short term control, about a few minutes, of the cardiovascular system, which is assumed by the nervous system, more precisely by its autonomic part (ANS) [74] and [75]. This short term control involves fast mechanisms of blood flow and pressure regulation, the baroreceptor control loop, neglecting slower ones, such as hormonal regulation. A good autonomic function is of crucial importance for life and is of great prognostic value in many diseases.

Models of the electro-mechanical activity of the cardiac muscle are very useful at the scale of the cardiovascular system as well as at the organ scale. In this later case, they are used for computing stress, strain and action potential fields from three-dimensional image processing. We have developped a chemically-controlled constitutive law of cardiac myofibre mechanics devoted to be embedded into macroscopic models. This law ensues from the modelling of the collective behaviour of actin-myosin molecular motors converting chemical into mechanical energy. Here this model is embedded into a lumped parameter model of the heart and used into a simulator of the cardiovascular system.

A new model of vascular compartments is currently developped. Compared to classical Windkessel models, it will be able to take into account some nonlinear phenomena like the dependence of the Pulse Transit Time (PTT) upon the pressure. Model-based analysis of PTT and distal arterial pressure may be useful for the non-invasive determination of arterial wall properties.

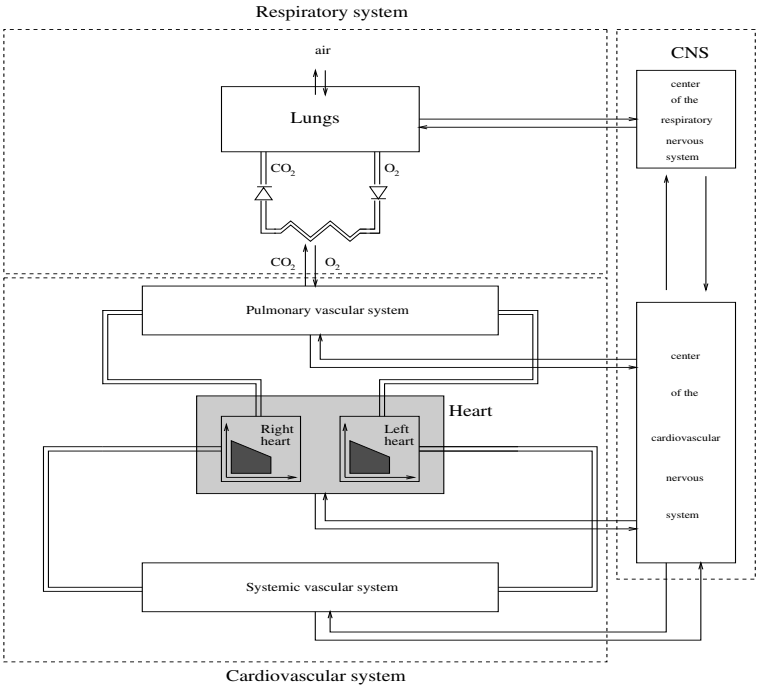

Figure 1. Model of cardiorespiratory system. Different systems interact to supply tissues with oxygen: respiratory, vascular (systemic and pulmonary), central nervous system and heart.

6.2.3. Mathematical modelling of arrhythmias in a system of coupled ischemic and normal cardiac ventricular cells

Participant: Mayer Landau.

The general framework of this study is mathematical modelling in cardiac electrophysiology. Mathematical non-linear analysis methods are used to study the different response patterns of a system of a coupled, normal cell and a pathological one, depolarized by an added steady current I. The intensity of the injury current I represents the degree of ischemia. Continuation-bifurcation technics are used to evidence turning points and Hopf bifurcation points, which are critical values of I limitating various behavioural zones of the system.

We found three possible levels for the resting potential of the system, with complex multistability phenomena between these levels. In the low level zone, we evidenced Unidirectional Block (UB) patterns in a window of depolarization thresholds or above a unique threshold depending of the value of the coupling resistance. Periodic branches of solutions emerge from the two Hopf bifurcation points corresponding to Ectopic Foci (EF) patterns coexisting with medium or high levels of stationary solutions. In these zones, we found again UB phenomena but, with locking of the system to a rhythmic solution, when the action potential propagates. This study presents a system where we met, in a single framework, eigher UB or EF by only changing I representing the level of ischemia of the pathological cell.

Groups of cells evidencing UB phenomena, are then included in a ring-shaped, one-dimensional, system of cardiac fibers. We are thus able to study reentreis phenomena (movement), and complex fibrillation behaviors corresponding to their interplay with EF.

6.2.4. Instantaneous parameter estimation in cardiovascular time series by harmonic and time-frequency analysis

Participants: Claire Médigue, Yves Papelier.

Time-frequency distributions, such as smoothed pseudo Wigner-Ville distribution (SPWVD), and complex demodulation (CDM), provide useful time-varying spectral parameter estimators. However, each of these methods has limitations that a joint utilization could largely reduce, due to their interesting complementary features. The aim of this research is to validate the joint SPWVD-CDM method on synthetic and real cardiovascular time series with normal and reduced variability such as in autonomic blockade or autonomic deficiency [20]. We propose two indexes related to the noise present in the signal and to the dispersion of the power spectrum in order to validate instantaneous parameter estimation. In the low-frequency band, the interpretation of the instantaneous frequency and phase of cardiovascular time-series should be discarded in many real-life situations. Conversely, in the high frequency band, under paced breathing, the reliability of the instantaneous parameters is demonstrated even in conditions of reduced cardiovascular variability.

6.3. Clinical and physiological applications

Participants: Frédérique Clément, François Cottin, Claire Médigue, Yves Papelier.

6.3.1. Heart rate variability during exercise performed above ventilatory threshold

Collaboration with the LIGE[1].

Purpose. To examine if differences in heart rate variability (HRV) could distinguish sub- from supra-ventilatory-threshold exercise and whether the exercise duration at supra-threshold intensity alters the cardio-respiratory synchronization.

Methods. Beat-to-beat RR interval, VO2, VCO2, VE and blood lactate concentration of eleven healthy well-trained pubertal subjects were collected during two exercise bouts: 1) Moderate : fifteen minutes performed below the power at ventilatory threshold (pVT). 2) Heavy : above pVT until exhaustion. Fast Fourier Transform, Smoothed Pseudo Wigner-Ville Distribution and Complex Demodulation were applied to RR time series.

Results. 1) Moderate exercise shows a prevalence of the LF spectral energy compared to the HF one (80 $\pm$ 10 % vs. 20 $\pm$ 10 %, $p < 0.001$), whereas the inverse proportion is observed during heavy exercise (11 $\pm$ 8 % vs. 89 $\pm$ 8 %, $p < 0.001$). 2) During heavy exercise, the HF amplitude in RR and the tidal volume (Vt) remain constant whereas the breathing frequency (BF) and heart rate (HR) both increase. Despite RR series and breathing signal remain synchronized, HR/BF ratio decreases and becomes stabilized at 3 RR for 1 breathing cycle, whatever the initial ratio.

Conclusion. 1) heart rate variability (HRV) allows to distinguish sub- from supra-ventilatory-threshold exercise 2) exercise duration at supra- threshold intensity does not alter the cardio-respiratory synchronization as evidenced by constant CR phase [33].

6.3.2. Comparison of HR and $\dot{V}O2$ kinetics during square-wave exercise in human

Collaboration with the LIGE.

At the onset of a moderate aerobic exercise (i.e. under the ventilatory anaerobic threshold - VAT), VO2 rises mono-exponentially until a VO2 steady state is reached. Instead, if work rate is likely to elicit a submaximal VO2 above VAT, VO2 first rises mono-exponentially during a phase (fast component - FC) and then increases more progressively (slow component - SC) until VO2max is reached or exhaustion occurs. Height men performed a cycle ergometer exercise at the work rate corresponding to the midway between pVAT and pVO2max (Pdelta50). RR kinetics was fitted by a bi-exponential decreasing regression model and VO2 kinetics by a bi-exponential increasing regression model with or without time delay (TD) for the SC. Adding the delay did not improve VO2 data fit. The FC time constant of RR kinetics was significantly lower than that of VO2 kinetics (22.2$\pm$7.6 vs. 33.7$\pm$4.7 s - mean$\pm$SD) whereas the SC time constant of RR kinetics was significantly greater than that of VO2 kinetics (2750$\pm$1250 vs. 541$\pm$722 s). The delay between RR and VO2 FC time constants is compatible with a feedforward mechanism (i.e. cardiovascular system entailing VO2) while that between RR and VO2 SC time constants is compatible with a feedback originating from active muscle (i.e. increasing muscle metabolism entailing cardiovascular system) [66].

[1] Laboratoire Interaction Génétique Entraînement, Université d'Evry

6.3.3. Heart rate variability in elite horse during interval training

Collaboration with the LIGE.

This study examines difference in horse's heart rate variability (HRV) between three different trotting velocities (Warm-up, Heavy exercise, Recovery) and between two heavy exercise repetitions respectively at the beginning and the end of an interval training session. Beat-to-beat RR interval of ten elite trotters were collected during two different training sessions for each horse. From heavy exercise to recovery, HRV spectral analysis revealed: first, a significant increase in total and in low frequency energy whereas high frequency energy decreased and second, a prevalence of HF energy compared to LF (LFn: 16 ± 8 % vs. HFn: 84 ± 8 %, $p < 0.001$), whereas inverse proportion is observed during recovery (LFn: 88 ± 11 % vs. HFn: 12 ± 11 %, $p < 0.001$). HF energy increases with exercise repetition at the same mean HR. The more the HR increases, the more HF energy increases and LF energy decreases. Determinants of the HRV observed at heavy exercise are in all probability of non-neural origin. A mechano- electric feed-back to the sinus node is conceivable [63].

6.3.4. Cardiac autonomic control during balloon carotid angioplasty and stenting

Hemodynamic alterations during balloon carotid angioplasty (BCA) and stenting have been ascribed to the consequences of direct carotid baroreceptor stimulation during balloon inflation. BCA with stenting in patients with carotid atheromatous stenoses offers a unique opportunity for elucidating the cardiovascular autonomic response to direct transient intravascular stimulation of the baroreceptors. We analysed the consequences of BCA on the autonomic control of heart rate and on breathing components in nine patients with atheromatous stenoses involving the bifurcation and the internal carotid. A time-frequency domain method, the smoothed pseudo-Wigner-Ville transform (SPWVT), was used to evaluate the spectral parameters (i.e., the instantaneous amplitude and centre frequency (ICF) of the cardiovascular and respiratory oscillations). Those parameters and their dynamics (8 and 24 h later) were evaluated during and after the procedure. BCA stimulates baroreceptors in all patients, which markedly reduces heart rate and blood pressure. Vagal baroreflex activation altered the respiratory sinus arrhythmia in terms of amplitude and frequency (ICF HF RR shifted from 0.27 +/- 0.03 to 0.23 +/- 0.04 Hz pre-BCA vs. BCA, respectively; $p < 0.01$). Both the high- and low-frequency amplitudes of heart rate oscillations were altered during carotid baroreceptor stimulation, strongly supporting a contribution of the baroreflex to the generation of both oscillations of heart rate. Carotid baroreceptors stimulation increased the inspiratory time (Ti) (1.5 +/- 0.5 to 2.3 +/- 0.6 s pre-BCA vs. BCA, respectively; $p < 0.01$). In awake patients, BCA with stenting of atheromatous stenosis involving the bifurcation and internal carotid causes marked changes in the cardiac autonomic and respiratory control systems [41].

6.4. Modelling, control and biosciences: ovulation control

This work has been undertaken within the framework of the ACI RNTS REGLO: "Ovulation control". See http://www-rocq.inria.fr/who/Frederique.Clement/reglo.html

6.4.1. Multi-scale modelling of the selection of ovulatory follicles

Participants: Frédérique Clément, Nki Echenim, Michel Sorine.

This work has been undertaken within the framework of a DEA (*Automatique et Informatique industrielle, Lille 1*) training course and is currently the matter of a PhD thesis. By now, the mathematical models interested in follicular development could be cast into two approaches. One focuses on the mechanims underlying follicular development, on the molecular and cellular scales and considers separately either ovulatory or atretic (degenerating) paths. The other focuses on the selection process by itself which is investigated in the sense of population dynamics. Our work has consisted in merging the mechanistic and multi-scale features of the former approach with the ability of the latter "to make peaks arise" within a distribution. Ovarian follicles are characterised by a density function describing the cell population constituting the follicular granulosa tissue, $\phi_i(\xi; a, \gamma, t)$, where ξ refers to the follicle, a represents the cytological age and γ the cellular maturity (i indexes the cell cycle phase). The conservation law for ϕ_i reads :

$$\frac{\partial \phi_i}{\partial t} + \frac{\partial (f_{ci}\phi_i)}{\partial \gamma} + \frac{\partial \phi_i}{\partial a} = G_i(\phi_1 ... \phi_N) - L_i(\phi_1 ... \phi_N) \tag{4}$$

We have so far determined the relevant i phases and specified the various terms (gain, loss, maturity velocity) of this equation, as well as the nature and shape of the control intervening in those terms and amounting to introduce interactions terms between follicles. The numerical simulation has been conducted in the simplified case of one follicle subject to constant control; it remains to be improved and generalised to the case of several interacting follicles.

6.4.2. Modelling of the ovarian function by means of Petri net formalism

Participants: Frédérique Clément, Frédéric Rolin.

This work has been undertaken within the framework of a DEA (Informatique Médicale et Technologies de la Communication, Paris 6) training course. Petri nets (in their extended sense including timed and stochastic Petri nets) constitute a powerful formalism for knowledge integration for which many implementation and analysis tools are available, and whose principles are easily accessible to non-specialists. The whole components of the female gonadotrope axis (hypothalamus, pituitary gland and ovaries with follicles and corpus luteum at different development stages) have been taken into account, thanks to a modular approach allowing to identify and describe subnets, while maintaining their ability to interact within the global net. The work steps have consisted, on the one hand, in formalising and writing-down the static nets, and, on the other hand, in simulating dynamically the firing of the net transitions. The main results have concerned the hypothalamo-pituitary part of the net, in which the features of the steroidal feedback on gonadotrophin and GnRH secretion have been introduced (range and frequency characteristics of LH pulsatility, conditions for the ovulatory surge).

7. Contracts and Grants with Industry

7.1. Reduced order models of Homogeneous Charge Compression Ignition (HCCI) engines

Participants: Fadila Maroteaux, Jean-Baptiste Millet, Michel Sorine.

Renault contract 1 02 D0667 00 21102 01 2. J.B. Millet is preparing his PhD in the framework of this CIFRE contract.
Homogeneous charge compression ignition (HCCI) is a new combustion technology that appears as a possible alternative to diesel engines with high efficiency and low pollutant emissions (mainly NO_x and particulate matter). It is based on auto-ignition as in the case of conventional diesel engines, but here auto-ignition is controlled, and so this type of engine is, in some sense, in the middle way between diesel and spark-ignition engines. Auto-ignition control is a new problem for automatic control engineers. The objective here is to develop reduced order models of the controlled auto-ignition process that will be useful to design control strategies.

7.2. Mathematical modelling and control of a reformer stage for a fuel cell vehicle

Participants: Karim Bencherif, Michel Sorine.

Renault contract 1 00 D0256 00 21102 012. K. Bencherif is preparing his PhD in the framework of this CIFRE contract.
The polymer electrolyte fuel cell (PEMFC) has a high energy conversion efficiency and zero pollutant emission when fueled with hydrogen. It is then one of the most promising candidates for fuel cell powered vehicles. Hydrogen can be stored or produced onboard the vehicle by reforming methanol or hydrocarbon fuels. Our research focuses on modelling and control of fuel cell systems comprising a PEMFC with an hydrocarbon reformer that produces hydrogen when needed. We have obtained reduced order models for this type of

systems, that can be used for the control of CO concentration at the reformer outlet. Controllers and observers have been designed and their performances tested with simulations.

7.3. Modelling and compensation of backlash in power transmission systems

Participants: Giancarlo Ferrari Trecate, Mehdi Gati, Michel Sorine.

Renault contrat 1 04 D0004 00 21102 012. M. Gati is preparing his PhD in the framework of this CIFRE contract.
Gear trains are used to convert the high speed - low torque output of the engine into a lower speed - higher torque input to the wheels. These transmissions systems have two main disadvantages: 1) contact between rotating parts may be lost somewhere along the kinematic chain during some transients, this is the backlash effect; 2) some undesired compliance is introduced into the system. Our objective is the suppression of the transient vibrations induced by the combined effect of backlash and compliance. The existence of contact and non-contact phases leads us to adopt an hybrid-system point of view for modelling and backlash compensation. Also we exploit the fact that backlash is a particular case of hysteresis [72].

8. Other Grants and Activities

8.1. National grants

8.1.1. ACI SCARAMOCO (Système CArdio-Respiratoire : Approche MOdélisation et COmmande)

Participants: Pierre-Alexandre Bliman [action coordinator], Jean Clairambault, Daniel Claude, Frédérique Clément, Emmanuelle Crépeau-Jaisson, Claire Médigue, Michel Sorine.

See http://www-rocq.inria.fr/sosso/ACI/scaramoco.html

8.1.2. ACI REGLO (REGulation de L'Ovulation)

Participants: Daniel Claude, Frédérique Clément [action coordinator], Claire Médigue, Michel Sorine.

See http://www-rocq.inria.fr/who/Frederique.Clement/reglo.html

8.1.3. Cooperative Research Action ICEMA-2 (Images of the Cardiac Electro-Mechanical Activity)

Participants: Frédérique Clément [action coordinator], Claire Médigue, Michel Sorine.

See http://www-rocq.inria.fr/who/Frederique.Clement/icema.html)
and http://www-rocq.inria.fr/sosso/icema2/icema2.html

8.1.4. Cooperative Research Action GDyn (Dynamical analysis of genetic regulatory networks)

Participants: Frédérique Clément, Giancarlo Ferrari Trecate, Michel Sorine.

See http://www-sop.inria.fr/comore/arcgdyn/arcgdyn.html

8.2. European grant

8.2.1. TMR Nonlinear Control Network, Control Training Site

Participants: Pierre-Alexandre Bliman, Michel Sorine.

The Nonlinear Control Network is funded by the European Commission's Training and Mobility of Researchrs (TMR) Programme. We participate to the Training Programme (M. Sorine: Lectures on friction modelling and control of systems with friction). P.A. Bliman is the coordinator for our participation.

8.2.2. NoE proposal HYCON

Participants: Giancarlo Ferrari Trecate, Michel Sorine.

G. Ferrari Trecate is the coordinator of the INRIA team participating to the Network of excellence HYCON ("Taming Heterogeneity and Complexity of Networked Embedded Systems" - submitted in the context of the second IST call within the Sixth Framework Programme).

8.3. International cooperations

8.3.1. Lyapunov Institute project

Participants: Giancarlo Ferrari-Trecate, Claire Médigue, Michel Sorine, Alexander A. Zhdanov.

Simulation of the control of the cardio-vascular system by means of a neuron-like Autonomous Adaptive Control (AAC) system.

This is a joint Project between INRIA, and ISP RAS, Russia (http://www.ispras.ru). The goal is a better understanding of the control of the cardio-vascular system. The control in human body is the privilege of special areas of the nervous system. The main idea of the project is to model the controlled cardiovascular system by connecting two models: the mathematical model of cardiovascular system developped in the project and a model and a simulator of the autonomous nervous system ("Autonomous Adaptive Control system" (AAC)), developped at ISP RAS. We expect that the resulting (rather complex) model will simulate important properties of cardiovascular system.

8.3.2. NSF Convention

Participants: Marianne Akian [Metalau project], Pierre-Alexandre Bliman [Responsible for INRIA], Michel Sorine.

A PICS convention CNRS-NSF on systems with delays (2002/2004).

8.3.3. Cooperation with IAS and Yzmir University

Participants: Giancarlo Ferrari-Trecate, Michel Sorine.

Participation to the research project "Satellite communications and related laboratories project" between the "Institut Aéronautique et Spatial" and the Yzmir University. In particular, G. Ferrari Trecate and Y. Sorel (Aoste project) supervised part of the Ph.D. activities of Tolga Ayav, focusing on the analysis and tuning of scheduling techniques for imprecise computation models.

9. Dissemination

9.1. Scientific activity and coordination

9.1.1. Working group "Delay systems" of the CNRS

Pierre-Alexandre Bliman and Catherine Bonnet participate at the GdR meetings on a regular basis.

9.1.2. Working group "Pseudodifferential Operators and diffusive representation in modelling Control and Signal"

Catherine Bonnet and Michel Sorine are members of this group.
See http://www.laas.fr/gt-opd/

9.1.3. Working group "Hybrid systems" of the CNRS

Giancarlo Ferrari Trecate participates at the GdR meetings on a regular basis for all the project activities concerning hybrid systems.
See http://www.supelec-rennes.fr/sdh/welcome.html

9.1.4. Coordination activity

P.A. Bliman:
- coordination of SCARAMOCO working group,

http://www-rocq.inria.fr/sosso/ACI/scaramoco.html
- Local organization of IFAC workshop on Time-Delay Systems TDS'03 with Catherine Bonnet, Frédérique Clément, Giancarlo Ferrari-Trecate, Martine Verneuille.
- Member of International Program Committee of IFAC TDS'04, to be held in Leuven, Belgium.
- Responsible for INRIA Rocquencourt Research center, of the activities of the Multi-partner Marie Curie Training Site entitled Control Training Site (beginning in 2002).
- Responsible for INRIA of the activities of the grant PICS CNRS-NSF "Systèmes à retard" (2002/2004).
- Participation to french-polish cooperation Polonium (2002-2003).
- Coordination, with Prof. J. Nekovář (Université Paris VI), of a collection of books and funds, organized by SMF and SMAI, in aid of Charles University Library in Prague (Czech Republic) after August 2002 flood.

C. Bonnet:
- is in the board of directors of the French Mathematical Society, of the GDR MACS (Research group on modelisation analysis and tracking of systems of the CNRS) and of the association *Femmes et mathématiques* (Women and Mathematics). She is a member of the french piloting committee of the Helsinki group on Women and Science of the European commission.
- Member of the national organizing committe of the IFAC Workshop on Time-Delay systems TDS'03.

F. Clément:
- coordination of ICEMA-2 consortium.
http://www-rocq.inria.fr/sosso/icema2/icema2.html
- coordination of REGLO working group.
http://www-rocq.inria.fr/who/Frederique.Clement/reglo.html
- co-organisation of Iliatech day "Modélisation et Simulation pour la Médecine", October 21rd 2003, INRIA Rocquencourt.

G. Ferrari Trecate:
- Giancarlo Ferrari Trecate has been part of the International Program Committee for the IFAC Conference on Analysis and Design of Hybrid Systems, 16-18 June 2003, St. Malo. Within the same conference, he also organized the invited session "modelling and identification of hybrid systems".
See http://www.supelec-rennes.fr/adhs03/.
- From November 2002, member of the IFAC Committee on Power Plants and Power Systems.

M. Sorine has been a member of the International Program Committees for the IFAC TDS03 and CIFA 2004 conferences. He is the Projects committee chairman of INRIA Rocquencourt Research Unit.

9.2. Teaching activity

- P.A. Bliman: "Linear Matrix Inequalities and Control Theory" for 3rd year students at ENSTA.
- F. Clément: Educational training for the "Modelling and control of biological systems", module part of the "Master's Degree in BioInformatics and BioStatistics" (Paris 11 University), to be held during the second semester of the 2003-2004 academic year.
- G. Ferrari Trecate taught the courses "Asservissements nonlinéaires", (Maîtrise en Électronique, Électrotechnique, and "Systèmes hybrides" (DESS) at the Université Paris-Sud.
- M. Sorine: Lectures on "The cardiovascular system and its short-term control: modelling and signal analysis", Von Karman Institute, May 12-16, 2003.
Lecture on "Le coeur : modélisation et traitement du signal", Cours de l'Ecole Doctorale de Sciences Mathématiques de Paris Centre, September, 2003.

9.3. Seminars

- P.A. Bliman, Lecture at LAAS, Toulouse – Juin 2003

- F. Clément, “A control approach of the multi-scale modelling of excitation-contraction coupling”. Séminaire "Mathématiques, Biologie et Médecine" de l’Institut Henri Poincaré, February 25th 2003.
- M. Sorine, “Problèmes de modélisation et de contrôle pour l’étude du système cardiovasculaire”, Colloquium Math Appli, IMAG, April 17th, 2003.
“Multiscale modelling of excitation-contraction coupling in striated muscles. Application to the cardiovascular system”, Séminaires du Collège de France, December 5th, 2003.
“Problèmes de modélisation et de contrôle pour l’étude du système cardiovasculaire”, Centre d’Automatique des Mines, Fontainebleau, June 23rd, 2003.

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