INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team Sosso2

Applications and tools for automatic control

Rocquencourt

THEME BIO

Activity Report

2004

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1. Team

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Catherine Bonnet [Research Associate (CR) Inria, half-time since 01/10/03]
Frédérique Clément [Research Associate (CR) Inria]
Giancarlo Ferrari Trecate [Research Associate (CR) Inria]
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Emmanuelle Crépeau-Jaisson [Associate Professor, Versailles Saint-Quentin University, since October 2004]
Yves Papelier [Associate Professor, Paris XI University (Orsay) ("en délégation" since October 2004]
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2. Overall Objectives

Keywords: *bioenergetics*, *biology*, *cardiovcascular system*, *combustion engine*, *control*, *energetics*, *fuel cell*, *health*, *modelling*, *multi-scale systems*, *ovulation control*, *process engineering*.

The SOSSO2 team is involved in modelling, observation and control of natural or engineered feedback-controlled systems. The main emphasis, since the ICEMA research cooperative action, is on controlled multi-scale systems, in particular systems for energy conversion.
Some topics related to physiological systems are considered with applications to diagnosis and therapy:

- Modelling of the controlled chemomechanical conversion in the heart on the cell, the tissue and the organ scales ;

- Model-based non-invasive assessment of the function of the cardiac pump on the cardiovascular system scale ;
- Multi-scale modelling of the selection of ovulatory follicles.

Control of energy conversion is also considered in low-emission vehicles:

- Reduced-order multi-scale modelling and control of auto-ignition in internal combustion engines ;
- Modelling, control and monitoring of fuel-cell systems.

3. Software

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

Participant: Claire Médigue.

LARY_CR is a software package dedicated to the study of cardiovascular and respiratory rhythms, developed in the SCILAB_SCICOS scientific environment [72]. 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.

4. New Results

4.1. Control theory

Keywords: *LMI*, *hybrid systems*, *identification*, *robust control*, *stability*, *systems of agents*.

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

Participant: Pierre-Alexandre Bliman.

We have 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. The method permits to consider also general convex programming problems depending upon parameters, as shown in a joint work with C. Prieur.

Second, motivated by the previous result, we have pursued the study of methods for computing solution of LMIs depending polynomially upon parameters. Part of this study has been done with P. Tsiotras: an exact stability test for one-parameter polynomially-dependent linear systems has been proposed, with tight bounds on the LMI size.

4.1.2. Robust control of delay systems

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

We have been concerned this year with the analysis of two methods that have been used extensively in the feedback stabilization of delay systems, namely, PID controllers and coprime factorization controllers [60].

We began by considering the internal stabilization of dead-time systems with transfer function $e^{-sT}\dfrac{p(s)}{q(s)}$, where $T > 0$ and p and q are real polynomials satisfying $\deg p \leq \deg q$, by PID controllers with transfer function $K(s) = k_p + \dfrac{k_i}{s} + k_d s$ where k_p, k_i, and k_d are real coefficients. We were also able to treat various classes of retarded and neutral systems for the first time. The simplest case of such systems, $\dfrac{1}{\alpha s + \beta + (\gamma s + \delta)e^{-sT}}$ where α, β, γ, δ are real ($\gamma = 0, \alpha \neq 0$ corresponding to a retarded system and $\alpha, \gamma \neq 0$, to a neutral one), is fully described in [60]. Without giving a complete characterization of the values of k_p, k_i and k_d solving the problem, we obtained important information about the limitations of such controllers.

We considered then the coprime factorization approach, motivated by the well-known Youla parametrization of stabilizing controllers. This has been fairly completely analysed in the SISO case (see [5]), and we made this year some extensions to the multivariable case. Moreover we showed how the existence of a single stabilizing PID controller can be used to help with the difficulty of finding Bézout factors, and thus simplify the parametrization of the set of stabilizing controllers.

There are further open questions related to the assignment of (finitely many) poles of a retarded and neutral system, and these are a subject for further study. Also the existence of 'stability windows' phenomena (the fact that addition of delay can have a stabilizing effect) could improve some results and we are currently working on an automatic determination of such windows in collaboration with Fabrice Rouillier of the SALSA project.

4.1.3. Comparison of procedures for the identification of hybrid systems

Participant: Giancarlo Ferrari Trecate.

In recent years, a number of procedures have been proposed for the identification of hybrid systems. These algorithms perform various tasks such as the classification of the data points, the reconstruction of the mode dynamics and the estimation of the switching law between different modes of operation. The methods available in literature differ for various aspects including the rationale underlying the mode reconstruction, the capability of estimating the number of modes composing the hybrid system and the possibility of handling *a priori* information available for the experiment considered. Unfortunately, a thorough theoretical characterization of such identification algorithms is not yet available and an experimental assessment of the pros and cons of each method becomes of primary importance for the user. We compared four procedures for the reconstruction of Piece-Wise AutoRegressive eXogenous (PWARX) models: the clustering-based procedure, the bounded-error procedure, the algebraic procedure and the Bayesian procedure. Synthetic benchmark problems and various quantitative measures for the quality of the obtained models have been proposed. The robustness of algorithms to noise statistics, tuning parameters and under/over estimation of model orders has been discussed. Finally, the performance of the methods has been compared on the data-based modelling of the electronic component placement process in pick-and-place machines.

4.1.4. Self-organization in systems of mobile agents

Participants: Giancarlo Ferrari Trecate, Mehdi Gati.

Several natural systems are characterized by a large number of agents, interacting only locally, whose individual actions produce a macroscopic organized behavior. Examples of this phenomenon are the collective motion of flocks of birds or schools of fishes, the functioning of multicellular biological organisms and genetic networks. All the above mentioned systems exhibit an emergent behavior stemming from local and simple coordination rules among the entities.

We focused on understanding how group of man-made, mobile agents can use local coordination rules to self-organize in moving formations. Recent developments in the field of electronics and mechanics allow to construct small mobile entities like robots and unmanned air or underwater vehicles having on-board computing capabilities and communicating through wireless networks. However, the study of decentralized control laws capable to reproduce the self-organizing behaviors is still in its infancy. Apparently this goal relies on the availability of faithful mathematical models for coordination phenomena.

We have developed a methodological framework for the modelling and the control of mobile agents partially interconnected by communication networks. The network is modeled as an incomplete graph: the nodes represent the dynamical systems characterizing individual agents, and the edges capture the topology of the communication protocol. The overall system is modeled by means of Partial difference Equations (PdE) on graphs. PdEs are mathematical models strongly inspired to partial differential equations and provide an unified and compact description of agents interactions in space and time. Moreover, PdEs allow naturally to interpret self-organization phenomena in terms of well known laws of classical physics. For example, in the problem of flocking, agents alignment corresponds to heat diffusion in a room and the formation velocities profile plays the role of a temperature distribution. Cohesion and collision avoidance features can be obtained by analogy to some laws of non-linear elasticity.

4.1.5. Control of Real-Time Feedback Rate-Monotonic Schedulers

Participant: Giancarlo Ferrari Trecate.

This research focuses on the statistical analysis of an adaptive real-time feedback scheduling technique based on imprecise computations. We considered two-version tasks composed of a mandatory and an optional part to be scheduled according to a feedback control rate-monotonic algorithm. We considered the use of Proportional-Integral-Derivative (PID) control actions for deciding about the execution or rejection of the optional sub-tasks. By modelling the task execution times as random variables, we computed the probability density of the CPU utilization and derived conditions on PID parameters guaranteeing the stability of the overall system around a desired level of CPU utilization. This allowed us to highlight the tasks statistics and the scheduling parameters that affect critically stability. The analysis has been developed by first exploiting a number of simplifying assumptions that have been progressively removed. When the workload statistics are unknown or non-stationary, the results point out the benefits of an adaptive strategy for tuning the controller parameters. The parameters that play a role in designing an adaptive controller have been highlighted and discussed. The main results were also demonstrated through Monte Carlo simulations of the scheduling algorithm.

4.1.6. Control of some distributed-parameter Systems

Participant: Emmanuelle Crépeau-Jaisson.

Control of a clamped-free beam. Joint work with Christophe Prieur (SATIE-ENS Cachan and then LAAS). We have considered the problem of exact controllability of a clamped-free metallic beam by a piezoelectric actuator. We have used a Bernouilli-Euler model and applied the Hilbert Uniqueness Method (HUM) to this model. By the proof of new results on diophantine approximations, we have obtained the dependance of the space of exactly controllable initial data with the location of the actuator.

Control of the Korteweg-de Vries equation. Joint work with Jean-Michel Coron (université d'Orsay).
It has been proved by L. Rosier that the linearized KdV system around 0, that is

$$\left\{ \begin{array}{c} y_t + y_x + y_{xxx} = 0, \\ y(t,0) = y(t,2k\pi) = 0, \end{array} \right.$$

is not controllable. We have considered the non linear problem

$$\left\{ \begin{array}{c} y_t + yy_x + y_x + y_{xxx} = 0, \\ y(t,0) = y(t,2k\pi) = 0 \end{array} \right.$$

and tried to prove that the nonlinear term yy_x gives the local controllability around the origin. In fact we have proved the nonlinear term allows us "to go" in the 2 directions $\pm(1-\cos(x))$ which are missed by the linearized control system.

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

Keywords: *bioenergetics*, *biology*, *cardiovcascular system*, *health*, *heart*, *modelling*.

4.2.1. Introduction

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 have obtained 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. It is thermodynamically consistent and the resulting dynamics of sarcomeres is consistent with the "sliding filament hypothesis" of A. F. Huxley.

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

Participants: Pavel Krejčí, Michel Sorine.

This work started within the framework of the ICEMA-2 cooperative action (2002-2003).
http://www-rocq.inria.fr/sosso/icema2/icema2.html A new cooperative action is in preparation with the Inria projects EPIDAURE, MACS and REO.

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.
This year we have considered the mathematical analysis of the model used in ICEMA in the more simple case of a one dimensional geometry (1 D problem). We have proved the well-posedness of the model and some asymptotic behaviour results [57] (joint work with J. Sainte-Marie, MACS project and J.M. Urquiza, CRM, Montreal).

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

Participants: Frédérique Clément, Emmanuelle Crépeau-Jaisson, Karima Djabella, Claire Médigue, Yves Papelier, Michel Sorine.

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.

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) [70] and [71]. 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.

4.2.4. Reduced model of pulsatile flow in an arterial compartment and application to pressure estimation

Participants: Emmanuelle Crépeau-Jaisson, Claire Médigue, Yves Papelier, Michel Sorine.

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.

4.3. Clinical and physiological applications

Keywords: *Heart rate variability*, *cardiovcascular system*, *health*.

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

4.3.1. Heart rate variability during exercise performed above ventilatory threshold

Collaboration with the LIGE (Laboratoire Interaction Génétique Entraînement, Université d'Evry).

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 ± 10 % vs. 20 ± 10 %, $p < 0.001$), whereas the inverse proportion is observed during heavy exercise (11 ± 8 % vs. 89 ± 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.

4.3.2. *Effect of exercise intensity and repetition on heart rate variability during training in elite trotting horse.*

Collaboration with the LIGE.

RR intervals of ten elite trotting horses were recorded during an interval training session performed on track. This study examined two hypothesis. Firstly, like in humans, the hyperpnea combined with a decrease in cardiac autonomic control on heart rate during heavy exercise could result in a prevalence of high frequency heart rate variability. Secondly, this prevalence could increase with the heavy exercise repetition. Two exercise intensities were compared: moderate (ME) and heavy (HE). Furthermore, heavy exercise repetitions were compared between the beginning and the end of the interval training session. When comparing ME and HE periods: heart rate was significantly lower (155 $\pm$ 12 vs. 210±9 ms, P<0.001), LF spectral energy (0.04-0.2 Hz) was significantly higher (ME: 6.94±4.80 and HE: 0.24±0.14 $ms^2 Hz^{-1}$, P<0.001) whereas HF (0.2-2 Hz) was significantly lower (ME: 7.09±2.24 and HE: 10.60±3.64 $ms^2 Hz^{-1}$, P<0.05). In relative terms, ME showed similar results in both LFn (LF/LF+HF) and HFn (HF/LF+HF) whereas HE showed a large prevalence of HFn energy compared to LFn (P<0.001). The difference in LF/HF ratio between the two exercise conditions was significant (1.14 ±0.92 vs. 0.09 $\pm$ 0.12, P<0.001). Exercise repetition induced a significant increase in heart rate between the beginning and the end of the interval training session (207$\pm$10 beats.min-1 vs. 212$\pm$9 beats.min-1, P<0.001) whereas LF energy decreases (1.54$\pm$1.65 vs. 0.32±0.24 $ms^2 Hz^{-1}$, P<0.01) and HF energy remained constant (10.79±4.10 vs. 10.40±3.35 $ms^2 Hz^{-1}$, NS). This study confirmed the results observed in humans during heavy exercise conditions with a large prevalence of HF in contrast to LF, this prevalence increasing with exercise repetitions. The observed decrease in LF/HF ratio could provide an index of hyperpnea in horses during interval training.

4.3.3. *Cross Analysis of HR and VO2 kinetics during Square Wave Exercise in Humans: a Model of Cardiovascular Adjustments*

Collaboration with the LIGE.

At the onset of a moderate square wave exercise, VO2 rises exponentially (fast component ? FC) until a VO2 steady state is reached. Instead, for heavy exercise an additional slow increase in VO2 (slow component ? SC) occurs until exhaustion. The purpose of this study was to compare and analyze the VO2 and HR kinetics to have an insight into the mechanisms underlying these two kinetics. Eight healthy men performed a cycle ergometer exercise at the work rate corresponding to midway between the work rate at VAT and at VO2peak (Pdelta50). Gas exchange was measured breath by breath and RR period was computed from ECG and cardioratemeter. HR and VO2 kinetics were fitted by a bi-exponential regression model and, for VO2, with or without time delay for the SC occurrence. Adding the delay did not improve VO2 data fit. The FC time constant of HR kinetics was significantly shorter than that of VO2 kinetics (23.3±3.6 vs. 33.7±4.7 s; p < 0.01) whereas the HR and VO2 SC time constants were not significantly different (270±48.2 vs. 541±722 s). The shorter time constant of HR kinetics FC together with a fast change in arterio-venous O2 difference at the onset of exercise give an evidence for the role of HR kinetics in limiting the VO2 FC (feedforward). The modelled O2 pulse vs. HR reaches a plateau at 158±7.4 min(-1), showing that during SC phase any further increase in VO2 is only due to HR increase.

4.3.4. *Assessment of the ventilatory thresholds from heart rate variability during a cycloergometer exhaustive test in elite cyclists*

This study examined whether it is possible to assess ventilatory thresholds from heart rate variability analysis. Beat-to-beat RR interval, VO_2, VCO_2, V_E and blood lactate concentration of ten healthy well-trained professional cyclists were collected during an incremental test performed on cycloergometer until exhaustion. A time-frequency analysis, the so-called "Smoothed Pseudo Wigner-Ville Distribution" was applied to RR time series in order to compute usual HRV components vs. exercise intensity stages. Both curves of V_E/VO_2 and V_E/VCO_2 vs. exercise intensity stages were analyzed to detect the first (VT1) and the second

(VT2) ventilatory thresholds. For all subjects, visual examination of both V_E/$VO_2$and instantaneous High-frequency amplitude divided by RR interval ratio (HF/RR, HF: 0.15-*fmax* Hz) vs. time showed a synchronous abrupt increase, at the same exercise intensity level, giving the first ventilatory threshold (VT1). The second ventilatory threshold (VT2) was not detected in five subjects. Mean respiratory and HRV components were compared two minutes before (pVT_{-2}) and two minutes after (pVT_{+2}) VT1. Respiratory components increased (V_E/VO_2: 24.7±2 vs. 27.7±3.3 $L.L^{-1}O_2$, V_E/VCO_2: 25.8±2 .7 vs. 27.5±3.4 $L.L^{-1}CO_2$, $p<0.01$). For HRV, both LF and LF/HF decreased (LF: 0.94±0.65 vs. 0.42±0.28, LF/HF: 0.44±0.28 vs. 0.3±0.16, $p<0.01$) whereas both HF and HF/RR increased (HF: 2.62±1.12 vs. 2.84±1.2, $p<0.01$, HF/RR 0.007±0.003 vs. 0.008±0.003, $p<0.05$). The number of cardiac beats by breathing cycle decreased between pVT_{-2} and pVT_{+2} (HR/BF: 4.61±0.7 vs. 4.17±0.68, beats.breathing cycles^{-1}, $p<0.01$). In conclusion, it was possible to assess the first ventilatory threshold from heart rate variability time frequency analysis.

4.3.5. Baroreflex Sensitivity and Treppe effect during short exercise

Purpose: to assess the short term effects of one minute high intensity handgrip exercise, under vagal influence, on heart rate (HR) and arterial blood pressure (ABP). *Methods:* mean time series, power spectral values and spectral baroreflex sensitivity (BRS), seen as the controller gain between RR and ABP, were compared on eight subjects, at 40% of maximum voluntary contraction, between successive handgrip bouts (HG) and their recovery bouts.
Results: mean HR and ABP values are higher during HG, and they closely vary from the onset/offset of the HG, ABP changes following HR changes in a few seconds. Only RR spectral values fall during HG, leading to a drop of BRS.
Conclusion: 1- a massive vagal withdrawal opens the baroreflex loop at the atrial level, leading to fast HR increase but to HR variability and BRS falls. 2- changes in ABP amplitude seems to be only related to changes in cardiac frequency, that corresponds to the myocardium force-frequency relation (positive staircase or Treppe effect). This inotropic indirect effect of vagal withdrawal added to its chronotropic effect, allows the vagal nerve to anticipate in emergency the lower sympathetic activation.

4.3.6. Short term control of the cardiovascular system: Assessment with the isometric handgrip exercise

This study aims at assessing the short term control of the Cardio Vascular system (CV), through a physiological test which involves strictly autonomic response: the handgrip isometric exercise, under vagal influence during the first minute. CVS parameters are extracted from RR and the arterial blood pressure (ABP) signals, respectively giving frequency and amplitude information on the CVS. Mean time series, spectral values and baroreflex sensitivity (BRS), seen as the spectral controller gain between RR and ABP, help to approach the underlying mechanisms of the autonomic control. Results give evidence of two major effects:
- The relation between heart rate and contractility (positive staircase or Treppe effect).
- The drop of BRS, due to the decrease of heart variability.

4.4. Modelling, control and biosciences: ovulation control

Keywords: *health*, *ovulation control*.

This work has been undertaken within the framework of the REGLO working group: “Ovulation control”. See http://www-rocq.inria.fr/who/Frederique.Clement/reglo.html

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

Participants: Frédérique Clément, Nki Echenim, Michel Sorine.

The biological meaning of follicular development is to free fertilizable oocytes at the time of ovulation. The ovulation rate results from an FSH (Follicle Stimulating Hormone)-dependent follicle selection process. 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. We aim at merging the molecular and cellular mechanistic description introduced by the former approach with the competition process dealt with in the latter, using both multi-scale modelling and control theory concepts. Each ovarian follicle is described through a 2D density function, $\varphi_f(a, \gamma, t)$, giving an age and maturity-structured description of its cell population. The conservation law for φ_f reads:

$$\frac{\partial \varphi_f}{\partial t} + \frac{\partial (h_f \varphi_f)}{\partial \gamma} + \frac{\partial (g_f \varphi_f)}{\partial a} = G - L \quad (1)$$

where a represents the cytological age and γ the cellular maturity. A control term representing FSH signal intervenes in the aging (g_f) and maturation (h_f) velocities, gain (G) and loss (L) terms of this conservation law. The multi-scale feature of the model operates through the zero and first-order moments of the density, corresponding respectively to the total number of cells and global maturity in a follicle. Summing those moments on the whole population of follicles gives further information on the ovarian scale. The model accounts for the changes in the total cell number, growth fraction (proportion of proliferating cells in the whole population) and global maturity of both ovulatory and degenerating follicles for various intensities of the selection rate. The different selection process outputs (mono- or poly-ovulation, anovulation) predicted by the model are consistent with physiological knowledge regarding vascularisation, pituitary sensitivity to ovarian feedback and treatment with exogenous FSH.

4.5. Modelling and control of Homogeneous Charge Compression Ignition (HCCI) engines

4.5.1. Modelling of HCCI combustion using reduced chemical kinetics of n-Heptane with multidimensional code

Keywords: *combustion engine*, *control*, *energetics*, *modelling*, *process engineering*.

Participants: Ludovic Noël, Fadila Maroteaux.

In order to reduce significantly diesel engine emissions for the future regulations, research is heading towards alternative combustion modes, which allow a drastic reduction of engine-out emissions. One way to achieve these objectives can be to use homogeneous charge compression ignition (HCCI) combustion. HCCI operation is based on burning a homogeneous mixture of air fuel and burned gas (internal or external EGR) with reduced combustion temperatures. Furthermore, theoretically the HCCI process eludes locally lean high temperature regions and rich low temperature regions compared to the combustion process for conventional diesel engines, thereby reducing NOx and particulate matter (PM) formation. Many studies have confirmed that during this mode the combustion process is mainly controlled by chemical kinetics. On another hand, the heat release during the HCCI combustion for most fuels occurs in two stages; the first stage is associated with low temperature kinetic reactions (or cool flame) and the time delay between the first stage and the main heat release (or second stage) is due to the negative temperature coefficient regime (NTC). The main issue is then to control the start of ignition and the rate of heat release over a wide range of engine operating conditions. Therefore, there is no direct control method as in spark ignition or conventional diesel engines.

In order to implement this combustion process in production engines, it is thus necessary to achieve more accurate analysis of homogeneous combustion by multidimensional simulation. The simulation of the homogeneous combustion mode as described above requires an accurate description of chemical reaction kinetics, especially for the description of low temperature reactions. However, a coupled CFD and detailed chemistry simulation requires substantial memory and CPU time which may be very difficult with current computer capabilities. Thus a reduced mechanism is required to simulate the engine cycle during this operating mode.

In this study three reduced mechanisms for n-heptane was developed using Chemkin code based on detailed mechanisms developed by Lawrence Livermore National Laboratory with 2446 reactions and 544 species, and by Chalmers University with 250 reactions and 57 species. The sensitivity analysis approach and the steady state approximation (QSS) were used to derive the reduced mechanisms for different engine applications, the three mechanisms are:

- 61 step mechanism (with 61 reactions and 37 species).
- 26 step mechanism (with 26 reactions and 26 species).
- Two steps mechanism (with 7 reactions and 14 species) with temperature criterion.

The two first mechanisms above have been implemented in a CFD code (Star-CD/Kinetics) in order to understand the effects of the main engine control parameters for homogeneous charge combustion. The main conclusions from this first part of our investigations on HCCI mode were:

- the rate of heat release is very steep for all the EGR rates investigated in this study;
- for very high charge dilution (EGR rate higher than 50 % and inlet temperature lower than 350K), a slow oxidation process occurs, with a very slow heat release, not adapted to engine operation;
- a high boost pressure enables HCCI combustion with high EGR rates;
- the HCCI combustion process is not efficient for equivalence ratios lower than 0.3 for air/fuel mixture when the inlet temperature slower than 350K.

In order to reduce combustion noise due to the steep heat release in consequence of the self massive auto-ignition of homogeneous charge, several methods based on stratification with different homogeneous zones have been studied. During this second part of our investigations, we have studied different types of stratifications: with EGR, with axial fuel distribution and radial fuel distribution, and temperatures. This step has shown that is difficult to reach the desired reduction of heat release rate, the most promising strategy is the radial fuel distribution. However, it is likely that the optimal fuel distributions depend on the engine operating conditions. In real engine configuration, the totally homogeneous charge cannot be realized, therefore the mixture heterogeneities will control the heat release rates as found during this study.

4.5.2. *Modelling of HCCI combustion: effects of chemical kinetics and turbulent mixing*

Participants: Ludovic Noël, Fadila Maroteaux, Michel Sorine.

The numerical modelling of complex turbulent flow is an important issue in engines applications. In order to investigate the effects of both the chemical kinetics and turbulent mixing, a stochastic model is used. At first a simple partially stirred plug flow (PaSPFR) is considered, where spatial homogeneity is assumed and were only two physical processes remain: chemical reaction and mixing. In the combustion chamber, local quantities are chemical species mass fractions and temperature and are assumed to be random variables (with their joint random vector). The time evolution of the mass density function (MDF) transport equation takes into account the terms representing the mixing properties and the reaction mechanism of the system. The two terms are approached by a stochastic process, the 26 reactions mechanism developed above is used to model the reaction term.

4.5.3. *Modelling of HCCI combustion: effects of NOx (NO and NO2) on auto-ignition*

Participants: Julia Hysenj, Fadila Maroteaux.

Several studies have shown that NOx accelerate the ignition of hydrogen and hydrocarbons meaning that NOx affect ignition chemistry. In SI engine knock investigations the amount of nitric oxide in the initial charge that gives a change of reactivity is around 1000 Ð 1200 ppm. However, the most important characteristic of HCCI process is that it can reduce NOx emissions by 90 Ð 98% in comparison to conventional Diesel combustion and the measured NOx emissions are very low (lower than 10 ppm). Unfortunately, no experimental data has been found yet in the literature for larger hydrocarbons such as n-heptane dealing with the effects of these species on the HCCI process. The question that follows from this is how the NOx affect the ignition of the HCCI process when the amount of this compound is lower than 10 ppm (depending on the quantities of EGR or RGF trapped).

In order to study numerically the effects of NOx on auto-ignition with homogeneous charges, several published NOx mechanisms have been tested. Those NOx mechanisms have been added to the 26-step mechanism and here again the Chemkin code has been used at constant volume simulations and during a compression and expansion cycle. This study has shown that when the amount of NOx added in the fresh mixture is lower than 1000 ppm there is no change of reactivity, meaning that the ignition delay times are equal to those obtained without NOx additions. For higher amount of NOx, we have obtained a slight difference in the low temperature regime. However, when only an amount of NO (greater than 100 ppm) is added to the fresh mixture, the ignition is advanced by 3 CA degrees during a compression and expansion cycle. The main attraction of the HCCI combustion is the very low NOx emissions (lower than 10 ppm), if those NOx are introduced in the combustion chamber by EGR, the results obtained here confirm that the ignition delay time is not affected.

5. Contracts and Grants with Industry

5.1. Reduced order models of 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.

In order to implement the HCCI combustion process in production engines, a reduced model of auto ignition is required for engine tuning. As we have seen above this combustion process is mainly controlled by chemical kinetics. The objective in this study is to develop reduced model to simulate the homogeneous combustion without taking into account the detailed kinetic process. A zero-dimensional model developed takes into account the amount of fuel present in the combustion chamber, the amount of fuel consumed by reactions and the evolution of the temperature in the system. This model has been written in order to reproduce the behavior of HCCI process in term of temperature evolution (or pressure evolution). This behavior evolves with two stable points and one unstable point; the first stable point is present in the cool flame region and the second stable point in the high regime region, the unstable point corresponds to the transition from the first state to the second state. The construction of this model has been based on the fundamental ideas of dynamics and bifurcations.

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

Keywords: *control*, *energetics*, *fuel cell*, *modelling*, *process engineering*.

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 [44], [43].

5.3. 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. See [12] for some first results in this direction. Also we exploit the fact that backlash is a particular case of hysteresis [69].

6. Other Grants and Activities

6.1. National grants

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

Participants: Pierre-Alexandre Bliman [action coordinator], Frédérique Clément, Emmanuelle Crépeau-Jaisson, Claire Médigue, Yves Papelier, Michel Sorine.

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

6.1.2. 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

6.1.3. Multi-scale imaging of the ovarian function

Participant: Frédérique Clément.

Research program supported by the Federative Research Institute on Functional Imaging (IFR135)
See http://ifr135.univ-tours.fr/

6.2. European grants

6.2.1. 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.

6.2.2. NoE 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") started on 15/09/04 in the context of the Sixth Framework Programme.

6.2.3. STREP HYGEIA

Participant: Giancarlo Ferrari Trecate.

G. Ferrari Trecate is the coordinator of the INRIA team participating to the Specific Targeted Research or Innovation Project HYGEIA ("Hybrid Systems for Biochemical Network modelling and Analysis") accepted in the context of the Sixth Framework Programme (starting date: 01/01/05).

6.3. International cooperations

6.3.1. NSF Convention

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

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

7. Dissemination

7.1. Scientific activity and coordination

7.1.1. Working group "Delay systems" of the CNRS

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

7.1.2. Coordination activity

P.A. Bliman:
- Member of International Program Committee of IFAC TDS'04, Leuven, Belgium.
- Coordination of "Action Concertée Incitative "Technologies pour la Santé" SCARAMOCO, Modélisation et commande de systèmes biologiques. Application au système cardio-respiratoire" (2001-2004).
http://www-rocq.inria.fr/sosso/ACI/scaramoco.html
- 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 fo INRIA of the activities of the grant PICS CNRS-NSF "Systèmes à retard" (2002/2004).
- Participation to french-polish cooperation Polonium (2002-2004).

C. Bonnet:
Is in the board of directors 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.

F. Clément:
- Coordination of REGLO working group.
http://www-rocq.inria.fr/who/Frederique.Clement/reglo.html
- Co-organisation of the CEA-EDF-INRIA school on "Electromechanical behaviour of the heart: confronting models with data towards medical applications", April 26-30 2004, INRIA Rocquencourt.
See http://www.inria.fr/actualites/colloques/cea-edf-inria/2004/electro.html
and http://www.inria.fr/actualites/colloques/cea-edf-inria/2004/progelectro.html
- Member of several recruitment and evaluation boards.

G. Ferrari Trecate:
- Member of the International Program Committee for the conference HSCC05 - Hybrid Systems: Computation and Control, Swiss Federal Institute of Technology (ETH) Zurich, Switzerland March 9-11, 2005.
- Member of the IFAC Committee on Power Plants and Power Systems.

M. Sorine:
- Member of the International Program Committees for the CIFA 2004 conference.
- Projects committee chairman of INRIA Rocquencourt Research Unit until september 2004.
- Head of the evaluation committee of the LAAS-CNRS (research groups of the section 07).
- Member of the scientific board of the "Pôle mécatronique du Mantois".

7.2. Teaching activity

- P.A. Bliman: “Linear Matrix Inequalities and Control Theory” for 3rd year students at ENSTA.
- F. Clément: “Modelling and control of biological systems”, course, part of the "Master’s Degree in BioInformatics and BioStatistics" (Paris 11 University).
- 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”, CEA-EDF-INRIA school on “Electromechanical behaviour of the heart: confronting models with data towards medical applications”, April 26-30 2004, INRIA Rocquencourt.
Lecture on “Le coeur : modélisation multi-échelle”, Cours de l’Ecole Doctorale de Sciences Mathématiques de Paris Centre, September, 2004.

7.3. Seminars

- P.A. Bliman, 5 lectures in Brasil: at State University of Campinas, Laboratório Nacional de Computação Científica (Petrópolis) and Universidade do Estado do Rio de Janeiro – April and December 2004 ; 2 lectures in USA at GeorgiaTech (Atlanta) – December 2004 ; 1 lecture in Università di Siena (Italy) – June 2004
- G. Ferrari Trecate, “Partial difference equations: a framework for coordination analysis in multiple agents formations”. Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, June, 23rd, 2004.
“Analysis of coordination of mobile agents through partial difference equations”. University of Cambridge, Cambridge, UK, October, 15th, 2004.
“Le equazioni alle differenze parziali: una metodologia per l’analisi di fenomeni di coordinazione in sistemi di agenti mobili”. Politecnico di Milano, Milano, Italy, November, 16th, 2004.
- M. Sorine, “Multiscale modelling of excitation-contraction coupling in striated muscles. Application to the cardiovascular system”, Versailles Saint-Quentin University, November 24th, 2004.
“The Heart: a distributed internal combustion engine”, GeoMath’04, a conference honoring Guy Chavent, Rocquencourt, December 9-10, 2004.

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