INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team BIPOP

Nonsmooth Dynamics and Optimization

Grenoble - Rhône-Alpes

THEME NUM

Activity Report

2008

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1. Team

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2. Overall Objectives

2.1. Introduction

Generally speaking, this project deals with nonregular systems, control, modelling and simulation, with emphasis on

- dynamic systems, mostly mechanical systems with unilateral constraints and Coulomb friction, but also electrical circuits with ideal diodes and transistors Mos[1], etc;
- numerical methods for nonsmooth optimization, and more generally the connection between continuous and combinatorial optimization.

2.2. Highlights of the year

Florent Cadoux won a Prize for the best poster presentation at Canum 2008. The monograph [1] has been published.

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[1] metal-oxyde semiconductor

3. Scientific Foundations

3.1. Dynamic non-regular systems

Keywords: *analysis*, *complementarity*, *control*, *convex analysis*, *impacts*, *mechanical systems*, *modeling*, *simulation*, *unilateral constraints*.

Dynamical systems (we limit ourselves to finite-dimensional ones) are said to be *non-regular* whenever some nonsmoothness of the state arises. This nonsmoothness may have various roots: for example some outer impulse, entailing so-called *differential equations with measure*. An important class of such systems can be described by the complementarity system

$$\begin{cases} \dot{x} = f(x,u,\lambda)\,, \\ 0 \leq y \perp \lambda \geq 0\,, \\ g(y,\lambda,x,u,t) = 0\,, \\ \text{re-initialization law of the state } x(\cdot)\ , \end{cases} \tag{1}$$

where $\perp$ denotes orthogonality; u is a control input. Now (1) can be viewed from different angles.

- Hybrid systems: it is in fact natural to consider that (1) corresponds to different models, depending whether $y_i = 0$ or $y_i > 0$ (y_i being a component of the vector y). In some cases, passing from one mode to the other implies a jump in the state x; then the continuous dynamics in (1) may contain distributions.
- Differential inclusions: $0 \leq y \perp \lambda \geq 0$ is equivalent to $-\lambda \in \mathrm{N}_K(y)$, where K is the nonnegative orthant and $\mathrm{N}_K(y)$ denotes the normal cone to K at y. Then it is not difficult to reformulate (1) as a differential inclusion.
- Dynamic variational inequalities: such a formalism reads as $\langle \dot{x}(t) + F(x(t),t), v - x(t) \rangle \geq 0$ for all $v \in K$ and $x(t) \in K$, where K is a nonempty closed convex set. When K is a polyhedron, then this can also be written as a complementarity system as in (1).

Thus, the 2nd and 3rd lines in (1) define the modes of the hybrid systems, as well as the conditions under which transitions occur from one mode to another. The 4th line defines how transitions are performed by the state x. There are several other formalisms which are quite related to complementarity. A tutorial-survey paper has been published [3], whose aim is to introduce the dynamics of complementarity systems and the main available results in the fields of mathematical analysis, analysis for control (controllability, observability, stability), and feedback control.

3.2. Nonsmooth optimization

Keywords: *Lagrangian relaxation*, *combinatorial optimization*, *convexity*, *numerical algorithm*, *optimization*.

Here we are dealing with the minimization of a function f (say over the whole space R^n), whose derivatives are discontinuous. A typical situation is when f comes from dualization, if the primal problem is not strictly convex – for example a large-scale linear program – or even nonconvex – for example a combinatorial optimization problem. Also important is the case of spectral functions, where $f(x) = F(\lambda(A(x)))$, A being a symmetric matrix and λ its spectrum.

For these types of problems, we are mainly interested in developing efficient resolution algorithms. Our basic tool is bundling (Chap. XV of [7]) and we act along two directions:

- To explore application areas where nonsmooth optimization algorithms can be applied, possibly after some tayloring. A rich field of such application is combinatorial optimization, with all forms of relaxation [9], [8].
- To explore the possibility of designing more sophisticated algorithms. This implies an appropriate generalization of second derivatives when the first derivative does not exist, and we use advanced tools of nonsmooth analysis, for example [10].

4. Application Domains

4.1. Introduction

Many systems (either actual or abstract) can be represented by (1). Some typical examples are:

- Mechanical systems with unilateral constraints and dry friction (the biped robot is a typical example), including kinematic chains with slack, phenomena of liquid slosh, etc.
- Electrical circuits with ideal diodes and/or transistors Mos.
- Optimal control with constraints on the state, closed loop of a system controlled by an MPC algorithm[2], etc.

This class of models is not too large (to allow thorough studies), yet rich enough to include many applications. This goes in contrast to a study of general hybrid systems. Note for example that (1) is a “continuous” hybrid system, in that the continuous variables x and u prevail in the evolution (there is no discrete control to commute from a mode to the other: only the input u can be used). Let us cite some specific applications.

4.2. Computational neuroscience

Modeling in neuroscience makes extensive use of nonlinear dynamical systems with a huge number of interconnected elements. Our current theoretical understanding of the properties of neural systems is mainly based on numerical simulations, from single cell models to neural networks. To handle correctly the discontinuous nature of integrate-and-fire networks, specific numerical schemes have to be developed. Our current works focus on event-driven, time-stepping and voltage-stepping strategies, to simulate accurately and efficiently neuronal networks. Our activity also includes a mathematical analysis of the dynamical properties of neural systems. One of our aims is to understand neural computation and to develop it as a new type of information science.

4.3. Electronic circuits

Whether they are integrated on a single substrate or as a set of components on a board, electronic circuits are very often a complex assembly of many basic components with non linear characteristics. The IC technologies now allow the integration of hundreds of millions of transistors switching at GHz frequencies on a die of 1cm^2. It is out of question to simulate a whole such IC with standard tools such as the SPICE simulator. We currently work on a dedicated plug-in able to simulate a whole circuit comprising various components, some modelled in a nonsmooth way.

4.4. Walking robots

As compared to rolling robots, the walking ones – for example hexapods – possess definite advantages whenever the ground is not plane or free: clearing obstacles is easier, holding on the ground is lighter, adaptivity is improved. However, if the working environment of the system is adapted to man, the biped technology must be preferred, to preserve good displacement abilities without modifying the environment. This explains the interest displayed by the international community in robotics toward humanoid systems, whose aim is to back man in some of his activities, professional or others. For example, a certain form of help at home to disabled persons could be done by biped robots, as they are able to move without any special adaptation of the environment.

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[2] model predictive control

4.5. Optimization

Optimization exists in virtually all economic sectors. Simulation tools can be used to optimize the system they simulate. Another domain is parameter *identification* (Idopt or Estime teams), where the deviation between measurements and theoretical predictions must be minimized. Accordingly, giving an exhaustive list of applications is impossible. Some domains where Inria has been implied in the past, possibly through the former Promath and Numopt teams are: production management, geophysics, finance, molecular modeling, robotics, networks, astrophysics, crystallography, ...Our current applicative activity includes: the management of electrical production (deterministic or stochastic), the design and operation of telecommunication networks.

4.6. Computer graphics Animation

A new application in Bipop is the simulation of complex scenes involving many interacting objects. Whereas the problem of collision detection has become a mature field those recent years, simulating the collision response (in particular frictious contacts) in a realistic, robust and efficient way, still remains an important challenge. Another related issue we began to study is the simulation of heterogeneous objects such as granular or fibrous materials, which requires the design of new high-scales models for dynamics and contacts; indeed, for such large systems, simulating each interacting particle/fiber individually would be too much time-consuming for typical graphics applications. Finally, our current activity includes the shape control of simulated objects, which is of great importance in the field of artistic design, for the making of movies and video games for example. Such problems typically involve constrained optimization.

5. Software

5.1. Nonsmooth dynamics: Siconos

Participant: Vincent Acary.

In the framework of the European project Siconos, Bipop was the leader of the Work Package 2 (WP2), dedicated to the numerical methods and the software design for nonsmooth dynamical systems. The aim of this work is to provide a common platform for the simulation, modeling, analysis and control of abstract nonsmooth dynamical systems. Besides usual quality attributes for scientific computing software, we want to provide a common framework for various scientific fields, to be able to rely on the existing developments (numerical algorithms, description and modeling software), to support exchanges and comparisons of methods, to disseminate the know-how to other fields of research and industry, and to take into account the diversity of users (end-users, algorithm developers, framework builders) in building expert interfaces in Python and end-user front-end through Scilab.

After the requirement elicitation phase, the Siconos Software project has been divided into 5 work packages which are identified to software products:

1. *Siconos/Numerics* This library contains a set of numerical algorithms, already well identified, to solve non smooth dynamical systems. This library is written in low-level languages (C,F77) in order to ensure numerical efficiency and the use of standard libraries (Blas, Lapack, ...)
2. *Siconos/Kernel(Engine + Front-End)* The Engine is an object-oriented structure (C++) for modeling and simulation of abstract dynamical systems. The Front-End is the driver interface of the Engine thanks to two types of API's. The first one is an API in C++, interfaced in Python for scripting uses. The second API, in C, will be interfaced with Scilab for a more user-friendly platform.
3. *Siconos/Analysis* This part is devoted to the stability and bifurcation analysis of nonsmooth dynamical systems.
4. *Siconos/Control* This part is devoted to the implementation of control strategies of non smooth dynamical systems.
5. *Siconos/*IMSE The final product is an Integrated modeling and Simulation Environment dedicated to applied nonsmooth problems.

Further informations may be found at http://siconos.gforge.inria.fr/

5.2. Humanoid motion analysis and simulation

Participant: Pierre-Brice Wieber.

The HuMAnS toolbox offers tools for the modelling, control and analysis of humanoid motion, be it of a robot or a human. It is a C/C++/Scilab/Maple-based set of integrated tools for the generation of dynamical models of articulated bodies with unilateral contact and friction, their simulation with an event-driven integration scheme, their 3D visualization, the computation of stability measures, optimal positions and trajectories, the generation of control laws and observers, the reconstruction of movements from different sensing systems.

5.3. Optimization

Participant: Claude Lemaréchal.

Essentially two possibilities exist to distribute our optimization software: library programs (say Modulopt codes), communicated either freely or not, depending on what they are used for, and on the other hand specific software, developed for a given application.

The following optimization codes have been developed in the framework of the former Promath project. They are generally available at http://irabot.inrialpes.fr/raweb.html; M1QN3 is also distributed under GPL.

5.3.1. Code M1QN3

Optimization without constraints for problems with many variables ($n \geq 10^3$, has been used for $n = 10^6$). Technically, uses a limited-memory BFGS algorithm with Wolfe's line-search (see Chap. 4 of [2] for the terminology).

5.3.2. Code M2QN1

Optimization with simple bound-constraints for (small) problems: D is a parallelotope in R^n. Uses BFGS with Wolfe's line-search and active-set strategy.

5.3.3. Code N1CV2

Minimization without constraints of a convex nonsmooth function by a proximal bundle method (Chap. XV of [7], Chap. 9 of [2]).

5.3.4. Modulopt

In addition to codes such as above, the Modulopt library contains application problems, synthetic or from the real world. It is a field for experimentation, functioning both ways: to assess a new algorithm on a set of test-problems, or to select among several codes one best suited to a given problem.

6. New Results

6.1. Modeling

6.1.1. Simulation of electrical circuits as nonsmooth dynamical systems

Participants: Vincent Acary, Olivier Bonnefon, Bernard Brogliato, Pascal Denoyelle.

DC-DC converters are usually difficult to simulate with classical tools like SPICE because of the highly nonlinear behaviour of some components and the frequent occurrence of intrinsically generated switching events.

The simulation of such circuits modelled as nonsmooth systems has been successfully achieved with a clear advantage over several SPICE simulators and a simulator belonging to the hybrid modelling approach.

6.1.2. Simulation of spiking neuronal networks

Participant: Arnaud Tonnelier.

The numerical simulation of neural networks requires special attention to reproduce accurately the firing times of spiking neurons, while allowing efficient simulation of large networks. Event-driven strategies have become increasingly popular since they allow the simulation of spiking neural networks exactly, with a computational cost similar to classical time-stepping schemes. Previous works were limited to linear integrate-and-fire neurons. In [38] we extend event-driven schemes to a class of nonlinear integrate-and-fire models. Results are presented for the quadratic integrate-and-fire model with exponential synaptic currents.

The development of an event-driven simulation algorithm has to be done case by case. In [25] we propose a generic technique, *voltage-stepping schemes*, that is based on a discretization of the voltage state-space of individual neurons. The new simulation strategy defines a local event-driven method inducing an implicit activity-dependent time stepping scheme. Long time-steps are used when the neuron is slowly varying, whereas small time-steps are used in periods of intense activity. Our method is illustrated on nonlinear integrate-and-fire models.

6.1.3. Neural dynamics

Participant: Arnaud Tonnelier.

The quadratic integrate-and-fire model (QIF) with adaptation is commonly used as an elementary neuronal model that reproduces the main characteristics of real neurons. In [26], we introduce a QIF neuron with a nonlinear adaptive current. This model reproduces the neuron-computational features of real neurons and is analytically tractable. It is shown that, under a constant current input, chaotic firing is possible. In contrast to previous studies, the neuron is not sinusoidally forced. We show that the spike-triggered adaptation is a key parameter to understand how chaos is generated.

6.1.4. Modeling and simulation of mechanical rods

Participant: Florence Bertails.

In Bertails's PhD thesis, a new dynamic model for an elastic rod was presented: the Super-Helix model, which stands for one of the most promising models for simulating non-stretchable rods that can bend and twist. However, this model suffers from a quadratic complexity in the number of discrete elements, which, in the context of interactive applications, makes it limited to a few number of degrees of freedom – or equivalently to a low number of variations in curvature along the mean curve.

In our recent work [14], we overcome this limitation by proposing a new, recursive scheme for the dynamics of a Super-Helix, inspired by the popular algorithm of Featherstone for serial multibody chains. Similarly to Featherstone's algorithm, we exploit the recursive kinematics of a Super-Helix to propagate element inertias from the free end to the fixed end of the rod, while the dynamics is solved within a second pass traversing the rod in the reverse way. Besides the gain in linear complexity, which allows us to simulate a rod of complex shape much faster than the original approach, our algorithm makes it straightforward to simulate tree-like structures of Super-Helices, which turns out to be particularly useful for animating trees and plants realistically, under large displacements. We are now looking at modeling contact and friction of thin rods with rigid objects.

6.1.5. Multiple impacts modelling

Participant: Bernard Brogliato.

The so-called Darboux-Keller approach for modelling simple impacts, is extended to the case of multiple impacts in [23] and [24]. A distributing law that accounts for the elasticity law is found, and combined with Stronge's energetic coefficient. Careful comparisions are made with experimental results found elsewhere in the physics and mechanical engineering literature on granular media, which show the validity of the model. The next step is the introduction of Coulomb's friction into the model.

6.2. Optimization

6.2.1. Nonsmooth analysis of spectral functions

Participant: Jérôme Malick.

Spectral functions are functions of matrices whose value at X depends only on the eigenvalues of X: a spectral function can be written $F = f \circ \lambda$, where f is a permutation-invariant function over R^n. A similar definition holds for sets.

A spectral function/set F inherits from many properties of the underlying function/set f, such as convexity and differentiability. We continue to build on this research line, connecting properties of a spectral function/set F and of the underlying function/set f, on two points:
– First, we prove in [18] that the property of prox-regularity [36] passes from f to F. To prove this result, we use the characterization of the subdifferential of those functions.
– Second, we prove in [30] that the spectral sets associated to smooth manifolds in R^n are themselves manifolds. This results looks simple but was extremely difficult to prove: we brace together tools from nonsmooth analysis, differential geometry, group theory and spectral analysis.

6.2.2. Advances on alternating projections theory

Participant: Jérôme Malick.

Alternating projections are simple and efficient methods to solve feasibility problems (that is to find a point in the intersection of several sets); they are widely used in engineering sciences. One striking example is to design “tight frames” [39]; there are many other applications in image processing, “compress sensing” in particular.

In several successful applications, linear convergence is observed, but not explained by the theory which focuses on alternating *convex* projections - whereas these applications require projections onto nonconvex sets.

Our paper [22] proves linear convergence of the method under very mild assumptions, namely that the intersection is *strong* (i.e. essentially “linearly regular”). Note that convexity is not necessary to get the local convergence result. The proof of these results rely heavily on tools from nonsmooth geometry [37].

6.2.3. Frictional contacts

Participants: Vincent Acary, Florent Cadoux, Claude Lemaréchal, Jérôme Malick.

We have designed a new algorithm to compute the Coulomb friction forces in a nonsmooth mechanical system; see [16]. The algorithm is hierarchical: in an inner stage, the sliding velocities are fixed and the corresponding forces are computed as solutions of a second-order cone program (a simple quadratic programming problem when the dimension is 2); in this formulation, the sliding velocities then have to satisfy a system of nonlinear equations, which is solved by a Newton method in the outer stage.

This approach has been implemented and compared with other ones, in particular [32] which we also improved by inserting a stabilizing device.

6.2.4. Telecommunication networks

Participants: Claude Lemaréchal, Georges Petrou.

To optimize a robust network when the unknown demands vary in a polyhedron (described by its inequalities), we have presented in [21] two algorithms, respectively computing upper and lower bounds of the optimal cost. The problem is definitely difficult (a minmaxmin problem) and the quality of the bounds is unpredictable in advance; they cannot even be assessed *a posteriori*: obtaining distant bounds does not imply that both bounds are bad. These two algorithms complete our work on the subject, finalized in Petrou’s thesis [11].

6.3. Control

6.3.1. Observer design

Participant: Bernard Brogliato.

The general problem of state observation for nonsmooth dynamical systems, or hybrid dynamical systems, remains largely open, in particular for systems whose trajectories may jump. In [31], [33] solutions are proposed for the design of asymptotic observers for various classes of nonsmooth systems (differential inclusions, complementarity systems). The problem of "closing the loop" (the separation principle) is also solved in particular cases.

6.3.2. Trajectory tracking

Participants: Bernard Brogliato, Constantin Morărescu.

In these works [35], [34] the problem of extending the so-called passivity-based controllers to Lagrangian systems with unilateral constraints is considered. The first work [35] treats fully actuated rigid systems. The second work [34] deals with the case when joint flexibilities are present. This is thought to be quite important since impacts are likely to excite vibrational modes and possibly destabilize the closed-loop system. We first derive a suitable stability criterion, then we design a switching control algorithm and numerical simulations are performed with the Moreau's time-stepping scheme of the SICONOS platform.

6.3.3. Optimal control

Participant: Bernard Brogliato.

The problem of quadratic optimal control with state inequality constraints is studied in [15], where the Pontryagin's necessary consitions take the form of a linear complementarity system (LCS). We take advantage of the formalism of the higher order Moreau's sweeping process [12], that is a distribution differential inclusions, to analyze this LCS. The work of ten Dam on the geometrical analysis of the positive invariance of systems with inequality state constraints is also used. Both frameworks allow us to better study the qualitative properties of the optimal trajectories.

6.4. Software development

6.4.1. Hair with contacts toolbox

Participants: Florence Bertails, Franck Pérignon.

In the context of the Cheveux ANR project, a new software interconnecting the hair simulation software (developed during F. Bertails's PhD thesis) and the Siconos platform is currently in progress. A first version has already been transferred to the software company BeeLight in charge of writing a Maya plug-in for hair modeling and dynamics, starting from our software. A collaborative environment allowing for exchanges between all partners of the Cheveux ANR project has also been set up, with the help of the Inria Gforge system.

6.4.2. Platform development: Siconos

Participants: Vincent Acary, Franck Pérignon.

The main achievements for the Siconos platform are

- *Siconos/Numerics*
  - Improvements and optimization of various numerical algorithms: frictional contact problem in two-dimensional and tree-dimensional configurations, nonsmooth solvers for block-structured problems, convergence tests based on Fischer-Bursmeister functions.
- *Siconos/Kernel*. Improvements and enhancements of
  - Modeling part: new Lagrangian relations, new first order dynamical systems;
  - Simulation part: time-stepping and event-driven schemes monitoring by an event stack and an event manager;
  - Control part: adding of control classes: actuators, sensors;
  - Optimization of the Siconos algebra class based on the Boost library http://www.boost.org/ ;
  - Example library.
- Improvements and extensions of the documentation: Getting Started Guide, Installation guide, User manual, Example manual and Theory Manual.

7. Contracts and Grants with Industry

7.1. Industrial contracts

ANR Cheveux: Modeling and dynamic simulation of hair in the context of feature films production.

Partners: Neomis Animation SARL, BeeLight SARL, Institut Jean Le Rond d'Alembert (UPMC-CNRS), Inria (Bipop, Evasion and Artis).

7.2. Other grants

– A common project named "VAL-AMS", dedicated to the high confidence validation of analog and mixed signal circuits was submitted by the Verimag laboratory, jointly with Inria-Bipop and LJK (laboratoire Jean Kuntzmann, Grenoble) as an answer to the ANR (Agence Nationale de la Recherche) call for projects on safety of computer systems. This project was selected by ANR last year.

Using this funding, a specialist engineer is working on the automatic equation-formulation of circuits as non smooth dynamical systems.
– ANR Slalom (Système de capteurs et logiciel d'animation permettant l'observation du mouvement d'un skieur freestyle), RNTL.
– ANR Guidage (Nouvelles stratégies pour le guidage et la commande de systèmes), BLAN NT05-1_43040.
– ANR Saladyn, COSINUS.
– ANR Multiple Impact, BLAN
– ANR Romeo.
–DGRST-INRIA, projet STIC 0711 with ENI Sfax (Tunisia).

8. Dissemination

8.1. PhD Theses

– Thesis of G. Petrou at the university of Paris 1 on: robust desing of telecommunication networks.

8.2. Software

– M2FC1 (a code for nonsmooth-nonconvex optimization) sent to Mentor Graphics (design of robust analog circuits).

8.3. Animation of the scientific community

B. Brogliato is:
– Associate Editor for Automatica (June 1999 to June 2005: Intelligent and Adaptive Systems; June 2005-June 2008: Nonlinear Systems and Control)
– Reviewer for Mathematical Reviews from 2001 to 2008
– Reviewer for ASME Applied Mechanics Reviews since 2001

F. Bertails has been a reviewer for
– ACM SIGGRAPH since 2007
– Eurographics since 2005
– ACM Solid and Physical Modeling Symposium since 2008.

She has been a member of the national SPECIF PhD award boarding since 2007.

B. Espiau is a member of
– the Steering Committees of Laas and Lirm,
– the Scientific Committee of JRL-France (Joint Robotics Laboratory),

8.4. Teaching

– UFR IMA, UJF Grenoble, (V. Acary, lectures on " Mathematical models for physics", 56h in Master 2)
– Ensimag, (V. Acary, lectures on " Modeling and simulation in Mechanics" 12h in third year, track Modeling and Scientific Computing; J. Malick, F. Cadoux: "Numerical Optimization", 54h and 64h respectively).

8.5. Invitation of specialists

– A. Daniilidis (Univ. Barcelona) 2 weeks;
– C. Liu (Univ. Peking), one month;
– Z. Zhai (Univ. Peking), one month.

8.6. Participation to conferences, seminars

– 12th Workshop on Combinatorial Optimization; Aussois, January (1 participant);
– Roadef - Groupe Mode 2007; Clermont-Ferrand, February (2 participants, 1 presentation);
– HSCC 2008; St Louis, Missouri, April (1 communication);
– CSMA Days; Nantes, April (1 communication);
– Advanced COmputational Methods in ENgineering (ACOMEN 2008); Liège, May (1 communication);
– Column Generation 2008; Aussois, May (1 participant);
– Canum 2008; St Jean de Monts, May (1 poster presentation);
– Foundations of Computational Mathematics; Hong Kong, June (1 communication);
– ENOC 2008; St Petersburg, June (2 communications);
– ACM SigGraph class on Hair Simulation (coorganization and 1 class: [29]);
– 8th World Congress on Computational Mechanics (WCCM8), 5th European Congress on Computational Methods in Applied Sciences and Engineeering (ECCOMAS 2008); Venice, July (1 communication);
– Gipsa Summer School: Optimization on manifolds; Grenoble, September (2 participants);
– 47th IEEE Conf. on Decision and Control; Cancun, Mexico, December (1 communication).
– Euromech Nonlinear Dynamics Conference ENOC 2008, St Petersburg, Russia, June/July (2 communications).
– Seminars in Bologna, Grenoble, Limoges, Louvain-la-Neuve, Univs. Paris, Polytechnique, Toulouse, Ecole Polytechnique de Tunis, GDR CNRS MACS (Paris).

9. Bibliography

Major publications by the team in recent years

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Year Publications

Doctoral Dissertations and Habilitation Theses

[11] G. Petrou. *Dimensionnement robuste des réseaux de télécommunication face à l'incertitude de la demande*, Ph. D. Thesis, univ. Paris 1, October 2008.

Articles in International Peer-Reviewed Journal

[12] V. Acary, B. Brogliato, D. Goeleven. *Higher order Moreau's sweeping process: Mathematical formulation and numerical simulation*, in "Mathematical Programming", vol. 113, n^{o} 1, 2008, p. 133-217.

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[15] B. Brogliato. *Some results on optimal control with unilateral state constraints*, in "Nonlinear Analysis, Theory, Methods and Applications", to appear, 2008.

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