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(Grenoble)**

Activity Report 2012

Project-Team BIPOP

Modelling, Simulation, Control and Optimization of Non-Smooth Dynamical Systems

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
**Modeling, Optimization, and Control
of Dynamic Systems**

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Project-Team BIPOP

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2. Overall Objectives

2.1. Overall Objectives

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 Mos¹, etc;
- numerical methods for nonsmooth optimization, and more generally the connection between continuous and combinatorial optimization.

3. Scientific Foundations

3.1. Dynamic non-regular systems

mechanical systems, impacts, unilateral constraints, complementarity, modeling, analysis, simulation, control, convex analysis

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

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

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 $-\lambda \in N_K(y)$, where K is the nonnegative orthant and $N_K(y)$ 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 [4], 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.

¹metal-oxyde semiconductor

3.2. Nonsmooth optimization

optimization, numerical algorithm, convexity, Lagrangian relaxation, combinatorial optimization.

Here we are dealing with the minimization of a function f (say over the whole space \mathbb{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 [10]) and we act along two directions:

- To explore application areas where nonsmooth optimization algorithms can be applied, possibly after some tailoring. A rich field of such application is combinatorial optimization, with all forms of relaxation [12], [11].
- 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 [13].

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, hair and fiber dynamics is another example).
- 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 algorithm², discontinuous feedback controllers like sliding-mode control, 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). The main tools for the analysis and simulation of such dynamical systems come from Convex Analysis, Non-smooth Analysis, Complementarity Theory (we make a strong use of complementarity problems solvers for numerical simulation), Variational Inequalities. 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.

²model predictive control

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.

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 frictionous 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. We also pursue some study on the design of high-order models for slender structures such as rods, plates or shells. Finally, our current activity includes the static inversion of mechanical 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 geometric fitting and parameters identification issues, both resolved with the help of constrained optimization.

5. Software

5.1. Nonsmooth dynamics: Siconos

Participants: Vincent Acary, Maurice Bremond, Olivier Bonnefon.

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** This module is an object-oriented structure (C++) for the modeling and the simulation of abstract dynamical systems. It provides the users with a set of classes to describe their nonsmooth dynamical system (dynamical systems, interconnections, nonsmooth laws, ...) and to perform a numerical time integration and solving.
3. **SICONOS/FRONT-END**. This module is mainly an auto-generated wrapper in Python which provides a user-friendly interface to the Siconos libraries. A scilab interface is also provided in the Front-End module.
4. **SICONOS/CONTROL** This part is devoted to the implementation of control strategies of non smooth dynamical systems.
5. **SICONOS/MULTIBODY**. This part is dedicated to the modeling and the simulation of multi-body systems with 3D contacts, impacts and Coulomb's friction. It uses the Siconos/Kernel as simulation engine but relies on an industrial CAD library (OpenCascade and pythonOCC) to deal with complex body geometries and to compute the contact locations and distances.

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. AMELIF

Participants: Pierre-Brice Wieber, François Keith.

The AMELIF framework is an integrative framework that proposes an API for the representation and simulation of virtual scenes including articulated bodies. AMELIF was devised to realize interactive scenario studies with haptic feedback while providing an interface enabling fast and general prototyping of humanoids (avatars or robots). It is entirely developed in C++ and is cross-platform. The framework is articulated around a core library, upon which several modules have been developed for collision detection, dynamic simulation (contact handling in a time stepping scheme), 3D rendering, haptic interaction, posture generation. This framework is developed mostly at the CNRS/AIST UMI JRL, but we started using it in the Bipop team and therefore started contributing actively to its development.

5.4. 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://www-rocq.inria.fr/~gilbert/modulopt/>; M1QN3 is also distributed under GPL.

5.4.1. 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 [3] for the terminology).

5.4.2. Code M2QN1

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

5.4.3. Code NICV2

Minimization without constraints of a convex nonsmooth function by a proximal bundle method (Chap. XV of [10], Chap. 9 of [3]).

5.4.4. 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.

5.5. MECHE: Simulation of fibrous materials

Participants: Florence Bertails-Descoubes, Alexandre Derouet-Jourdan, Romain Casati, Laurence Boissieux.

The software MECHE was essentially developed during the MECHE ADT (2009-2011), for simulating the dynamics of assemblies of thin rods (such as hair), subject to contact and friction. Currently, this software is extensively used by two PhD students (A. Derouet-Jourdan and R. Casati) and continues to be enriched with new rod models and inversion modules. This software combines a panel of well-accepted models for rods (ranging from reduced coordinates to maximal coordinates models, and including models recently developed by some members of the group) with classical as well as innovative schemes for solving the problem of frictional contact (incorporating the most recent results of the group, as well as the new contact solver we published in [8]). The aim of this software is twofold: first, to compare and analyze the performance of nonsmooth schemes for the frictional contact problem, in terms of realism (capture of dry friction, typically), robustness, and computational efficiency. A first study of this kind was conducted in 2010-2011 onto the different rod models that were available in the software. New studies are planned for evaluating further rod models. Second, we believe such a software will help us understand the behavior of a fibrous material (such as hair) through virtual experiments, thanks to which we hope to identify and understand some important emergent phenomena. A careful validation study against experiments started to be conducted in 2011 in collaboration with physicists from L'Oréal. Once this discrete elements model will be fully validated, our ultimate goal would be to build a continuous macroscopic model for the hair medium relying on nonsmooth laws. The core of this software was transferred to L'Oréal in 2011.

6. New Results

6.1. Multiple impacts modelling

Participants: Bernard Brogliato, Ngoc-Son Nguyen.

The work consists of studying two systems: the rocking block and tapered chains of balls, using the Darboux-Keller model of multiple impacts previously developed. The objectives are threefold: 1) show that the model predicts well the motion by careful comparisons with experimental data found in the literature, 2) study the system's dynamics and extract critical kinetic angles that allow the engineer to predict the system's gross motion, 3) develop numerical code inside the SICONOS platform that incorporates the model of multiple impact. Other works consist of analysing kinematic restitution laws based on the use of the kinetic energy metric. We also performed an analysis of the rocking block motion in terms of the kinetic angles between the two unilateral constraints. Results are in [21], [22] [55]. Another work is dedicated to analysing the influence of bilateral holonomic constraints on the well-posedness of the complementarity problem obtained from the (frictionless) unilateral constraints. Gauss' principle extension to this case is also analysed [20].

6.2. Discrete-time sliding mode control

Participants: Vincent Acary, Bernard Brogliato, Olivier Huber, Bin Wang.

This topic concerns the study of time-discretized sliding-mode controllers. Inspired by the discretization of nonsmooth mechanical systems, we propose implicit discretizations of discontinuous, set-valued controllers. This is shown to result in preservation of essential properties like simplicity of the parameters tuning, suppression of numerical chattering, reachability of the sliding surface after a finite number of steps, and disturbance attenuation by a factor h or h^2 [18]. In [23] we have provided a tutorial on similar types of systems like relay systems, and their relationships with other formalisms like complementarity systems, or switching dynamical systems. This follows in fact a research program proposed in [4].

6.3. Optimization

6.3.1. Optimization algorithms for large-scale machine learning problems, and applications in computer vision

Participant: Jérôme Malick.

This collaboration with Zaid Harchaoui (Inria, LEAR Team) has been growing since summer 2010. It also involves Miro Dudik (Microsoft Research NYC) and a student who just started his PhD in october 2012 (after his master with us).

The explosion of data that we are experiencing (Big Data) lead us to huge-scale learning problems, new challenges for statistical learning and numerical optimisation algorithms. For example, the new databases for image categorization are large-scale in the three dimensions (large number of examples, high-dimension feature description, and large number of categories). The resulting learning problem is out of reach by standard optimization problems.

We developed a new approach exploiting the hidden underlying lower-dimension structure of this big data. We proposed a new family of algorithms (of the type coordinate results, or conditional gradient), whose iterations have an algorithmic complexity lower than an order compared to standard methods. For example, applied to learning problems with trace-norm penalization, our algorithm [26] exploit the atomic decomposition of the norm and compute only an approximate largest singular vector pair (instead of the whole singular value decomposition). Promising results [27] have been obtained on the image database Imagenet, where we show significant improvements compare to the state-of-the-art approaches (one-vs-rest strategies).

6.3.2. Semidefinite programming and combinatorial optimization

Participants: Nathan Krislock, Jérôme Malick.

We have worked with Frederic Roupin (Prof. at Paris XIII) on the use of semidefinite programming to solve combinatorial optimization problems to optimality. Within exact resolution schemes (branch-and-bound), "good" bounds are those with a "good" balance between tightness and computing times.

We proposed a new family of semidefinite bounds for 0-1 quadratic problems with linear or quadratic constraints [50]. The paradigm is to trade computing time for a (small) deterioration of the quality of the usual semidefinite bounds, in view of enhancing this efficiency in exact resolution schemes. Extensive numerical comparisons et tests showed the superior quality of our bounds, when embedded within branch-and-bound schemes, on standard test-problems (unconstrained 0-1 quadratic problems, heaviest k-subgraph problems, and graph bisection problems).

We have embedded the new bounds within branch-and-bound algorithms to solve 2 standard combinatorial optimization problems to optimality.

- *Max-cut.* We developed [34] an improved bounding procedure obtained by reducing two key parameters (the target level of accuracy and the stopping tolerance of the inner Quasi-Newton engine) to zero, and iteratively adding triangle inequality cuts. We also precisely analyzed its theoretical convergence properties. We show that our method outperform the state-of-the-art solver ([52]) on the large test-problems.
- *Heaviest k-subgraph problems.* Our previous work [51] takes advantage of the new bounds in their basic form to prune very well in the search tree. Its performances are then comparable with the best method (based on convex quadratic relaxation using CPLEX as an engine). Adapting and incorporating the techniques we developed for the max-cut problem, we propose in [35] an big improvement of the first algorithm (up to 10 times faster). For the first time, we were able to solve exactly k-cluster instances of size 160. In practice, our method works particularly fine on the most difficult instances (with a large number of vertices, small density and small k).

Finally, we have worked on making our data sets available online together with a web interface for our solvers. We have also started working on a generic online semidefinite-based solver for binary quadratic problems using the generality of [50]. All this is publicly available on line at <http://lipn.univ-paris13.fr/BiqCrunch/>.

6.3.3. *Unified theory of inaccurate bundle methods*

Participants: Claude Lemaréchal, Welington Oliveira.

Convergence of bundle methods is an intricate subject. The situation is even worse in the inexact case, where many variants exist, each with its specific *ad hoc* proof techniques.

With C. Sagastizábal (Rio de Janeiro), we have developed a synthetic theory to single out the successive steps when proving convergence of a generic algorithm, as well as the specific hypotheses that they need. Our pattern covers all variants published so far and suggests a new one. The corresponding paper is being finalized.

6.3.4. *Stabilizing marginal prices in electricity production*

Participants: Claude Lemaréchal, Jérôme Malick, Sofia Zaourar.

Unit-commitment optimization problems in electricity production are large-scale, nonconvex and heterogeneous, but they are decomposable by Lagrangian duality. Realistic modeling of technical production constraints makes the dual objective function computed inexactly though. An inexact version of the bundle method has been dedicated to tackle this difficulty [48]. However, the computed optimal dual variables show a noisy and unstable behaviour, that could prevent their use as price indicator. We propose a simple and controllable way to stabilize the dual optimal solutions, by penalizing the total variation of the prices [36]. Our illustrations on the daily electricity production optimization of EDF show a striking stabilization at a negligible cost.

6.4. Robotics

6.4.1. *Hierarchic QP solver*

Participants: Pierre-Brice Wieber, Dimitar Dimitrov.

We are working in collaboration with the LAAS-CNRS and the CEA-LIST on solving multi-objective Quadratic Programs with Lexicographic ordering: Hierarchic QPs [47]. The focus this year has been on enabling fast computations in the case of time-varying Hierarchic QPs through warm-starting the active set method. This has been possible by developing an active set method for lexicographic multi-objective ordering [44], [45]. The main difference with respect to classical active set methods is in the use of a “lexicographic” (sometimes called “multi-dimensional”) Lagrange multiplier.

6.4.2. *Modeling of human balance in public transports*

Participants: Pierre-Brice Wieber, Zohaib Aftab.

Zohaib Aftab finished his PhD thesis in collaboration with IFSTTAR (previously INRETS) on modeling human balance in public transports. A Model Predictive Control scheme has been developed for the prediction of recovery motions, including ankle and hip strategies as well as stepping with adaptive step locations and timings [37]. This MPC scheme has been validated against a balance recovery scenario found in the biomechanics literature [38].

6.4.3. *Model Predictive Control for Biped Walking*

Participants: Pierre-Brice Wieber, Andrei Herdt, Jory Lafaye.

In collaboration with the DLR in Munich, we designed an MPC scheme for biped walking based on the “Capture Point”. This is just a simple change of variable $\xi = x + \frac{1}{\omega}\dot{x}$ that transforms the second-order dynamics of the Center of Mass x of the robot into a cascade of two first-order dynamics, one stable and one unstable. This MPC scheme has been evaluated successfully on the DLR biped robot [49].

Since fast computations are always a key objective for feedback controllers, we designed a change of variable in the underlying QP in order to expose the specific structure between time-varying and time-invariant parts of the Hessian matrix and compute its Cholesky decomposition in an efficient way by pre-computing the decomposition of the time-invariant part.

6.5. Computational Toxicology

Participant:

It is now well recognized that toxicology has entered a new era. Previously mainly based on animal testing, toxicology is now turning to *in vitro* and *in silico* experiments. To assess the risk of chemicals but also to gather and to interpret the massive amounts of experimental data generated by modern toxicology, the development of mathematical and computational tools are essential. An important element in risk assessment of chemicals is the human bioaccumulative potential. We developed a predictive tool for human bioaccumulation assesment using a physiologically based toxicokinetic model [53].

6.6. Computational Biology

Participant:

Biological oscillations have attracted widespread interest from experimentalists, with the *in vivo* design of synthetic oscillators, and from mathematicians, with the study of limit cycles. Oscillations in protein concentrations or gene expression are supposed to be involved in the generation of the rhythms observed in the cell. In many situations, oscillations are originated by negative feedback loops. In [54] we have studied the oscillatory regimes of a negative feedback oscillator and derived the probability of having oscillations.

6.7. Mechanical rods

6.7.1. *High-order models of mechanical rods*

Participants: Florence Bertails-Descoubes, Romain Casati.

Reduced-coordinates models for rods such as the articulated rigid body model or the super-helix model [39] are able to capture the bending and twisting deformations of thin elastic rods while strictly and robustly avoiding stretching deformations. In this work we are exploring new reduced-coordinates models based on a higher-order geometry. Typically, elements are defined by a polynomial curvature function of the arc length, of degree $d \geq 1$. The main difficulty compared to the super-helix model (where $d = 0$) is that the kinematics has no longer a closed form. Last year we investigated the clothoidal case ($d = 1$) in the 2d case [19], relying on Romberg numerical integration. This year, in R. Casati's PhD's thesis, we extended this result to the full 3D case. The key idea was to integrate the rod's kinematics using power series expansion, and to design an accurate and efficient computational algorithm adapted to floating point arithmetics. Our method nicely propagates to the computation of the full dynamic of a linked chain of 3d clothoid. All these results will we submitted for publication early 2013.

6.7.2. Inverse modeling of mechanical rods

Participants: Florence Bertails-Descoubes, Alexandre Derouet-Jourdan.

Controlling the input shape of slender structures such as rods is desirable in many design applications (such as hairstyling, reverse engineering, etc.), but solving the corresponding inverse problem is not straightforward. In [43] we noted that reduced-coordinates models such as the super-helix are well-suited for static inversion in presence of gravity. The main difficulty then amounts to fitting a piecewise helix to an arbitrary input curve. This year in A. Derouet-Jourdan's PhD's thesis, we solved this problem by extending to 3d the floating tangents algorithm introduced in 2d in [43]. In this new method, only tangents are strictly interpolated while points are displaced in an optimal way so as to lie in a feasible configuration, *i.e.*, a configuration that is compatible with the interpolation by a helix. Our method proves to be efficient and robust as it can successfully handle large and complex datasets from real curve acquisitions, such as the capture of hair fibers or the magnetic field of a star. This result was submitted for publication to Computer-Aided Geometric Design in Spring, and is currently under minor revision.

6.8. High-accuracy time-stepping schemes

Participant: Vincent Acary.

To perform the numerical time integration of nonsmooth mechanical systems, the family of event-capturing time-stepping schemes are the most robust and efficient tools. Nevertheless, they suffer from several drawbacks : a) a low-order accuracy (at best at order one), b) a drift phenomena when the unilateral constraints are treated at the velocity level and c) a poor "energetic" behavior in terms of stabilizing the high-frequency dynamics. We first proposed to improve the global order of accuracy over periods when the evolution is sufficiently smooth by mixing standard higher order schemes for Differential Algebraic equations and the Moreau-Jean's scheme [16]. We also proposed self-adapting schemes by applying time-discontinuous Galerkin methods to the measure differential equation in [24]. In order to satisfy in discrete time, the impact law and the constraints at the position and the velocity level, an adaptation of the well-known Gear-Gupta-Leimkuhler approach has been developed in [17]. Finally, the energetic behavior of the standard Moreau-Jean scheme has been addressed in [25] by developing a Newmark-type scheme for nonsmooth dynamics.

6.9. Dissipativity preserving methods

Participants: Vincent Acary, Bernard Brogliato.

This work concerns the analysis of so-called theta-methods applied to linear complementarity systems that are dissipative. Necessary and sufficient conditions for dissipativity preservation after the time-discretization are derived (preservation of the storage function, the supply rate and the dissipation function). The possible state jumps are also analyzed [46]. It is shown that excepted when the system is state lossless and $\theta = 0.5$, the conditions are very stringent.

6.9.1. Multivalued Lur'e dynamical systems

Participant: Bernard Brogliato.

Lur'e systems are quite popular in Automatic Control since the fifties. Set-valued Lur'e systems possess a static feedback nonlinearity that is a multivalued function. This study consists in the mathematical analysis (existence and uniqueness of solutions) and the stability analysis (Lyapunov stability, invariance principle) of classes of set-valued Lur'e systems, with applications in complementarity dynamical systems, relay systems, mechanical systems with dry friction, electrical circuits, etc. Our works in this field started in [40]. The results in [42] extend those in [41] with an accurate characterization of the maximal monotonicity of the central operator of these systems. Concrete and verifiable criteria are provided for the above classes (complementarity, relay systems).

7. Bilateral Contracts and Grants with Industry

7.1. CIFRE THESIS

7.1.1. *Schneider Electric*

Participants: Vincent Acary, Narendra Akadkhar, Bernard Brogliato.

This is a long-term relationship with this company, starting in 2001 with the post-doc of V. Acary. A PhD thesis funded by SE started in December 2012 (Narendra Akadkhar), co-supervised by V. Acary and B. Brogliato, and by M. Abadie (SE). The topic is about simulation of circuit breakers with mechanical play, and multiple impacts with friction modelling.

7.1.2. *ANSYS*

Participants: Vincent Acary, Mounia Haddouni, Bernard Brogliato.

This collaboration started in May 2012 with the CIFRE thesis of M. Haddouni. The topic is about numerical simulation of multibody systems with unilateral contact, impacts and friction.

7.1.3. *ALDEBARAN*

Participants: Pierre-Brice Wieber, Jory Lafaye.

This collaboration started in March 2012 with the CIFRE thesis of J. Lafaye. The topic is biped walking control schemes in dynamic environments.

7.1.4. *ADEPT*

Participants: Pierre-Brice Wieber, Saed Al Homsy.

This collaboration started in September 2012 with the CIFRE thesis of S. Al Homsy. The topic is fast reactive motion generation for manipulator robots.

7.2. Other contracts

7.2.1. *L'OREAL*

Participant: Florence Bertails-Descoubes.

L'OREAL: Contrat d'étude with L'Oréal, starting in December 2012 until April 2013 .

8. Partnerships and Cooperations

8.1. Regional Initiatives

Participants: Guillaume James, Vincent Acary, Franck Pérignon, Bernard Brogliato.

An IXXI project (institute for complex systems) has been accepted in November 2012. It concerns the study of nonsmooth mechanical systems with a particular focus on nonlinear waves, and nonlinear modes. Title: Ondes non linéaires dans les réseaux granulaires et systèmes mécaniques spatialement discrets.

8.1.1. ANR

- Project ChaSlim (01 October 2011–30 September 2015). Coordinated by Bernard Brogliato. Participants from BIPOP: V. Acary, O. Huber, B. Wang. Other partners: IRCCYN nantes and EPI NON-A from Inria Lille. Topic: reduction of chattering in sliding mode control (<http://chaslim.gforge.inria.fr/>)
- NSFC/ANR project Multiple Impact (01 January 2009 – 31 March 2012). Coordinated by B. Brogliato for the French side, and by C. Liu for the Chinese side. Participants from BIPOP: N.S. Nguyen.
- Project Saladyn (01 January 2009–31 December 2012). Coordinated by V. Acary. Participants from BIPOP: F. Pérignon, M. Brémond, B. Brogliato (<http://saladyn.gforge.inria.fr/>)
- Project Geolmi (January 2011– December 2014). Geometry and Algebra of LMI with Systems Control Applications. Participants from BIPOP: J. Malick (<http://homepages.laas.fr/henrion/geolmi/>)

8.1.2. Competitivity Clusters

- PSPC Project Romeo 2 (01 December 2012–01 December 2016). Topic: Development of a humanoid robot assistant and companion for everyday life. Participants from Bipop: P.-B. Wieber and D. Dimitrov.

8.2. International Initiatives

8.2.1. Participation In International Programs

- PHC Procope collaboration with DLR in Munich (Jan. 2012–Dec. 2013). Topic: Real-Time Optimization based Control of Bipedal Humanoid Robots. Participants from Inria: P.-B. Wieber, A. Herdt, J. Lafaye, D. Dimitrov.

9. Dissemination

9.1. Scientific Animation

- A. Tonnelier: Membre du CNU, section 26.
- F. Bertails-Descoubes has been a reviewer in 2012 for ACM SIGGRAPH, ACM Transactions on Graphics, and Eurographics.
- Jérôme Malick: Associate Editor for Journal of Global Optimization (Springer)
- P.-B. Wieber is member of the Program Committee of the IEEE-RAS International Conference on Humanoid Robots, reviewer for IEEE Transactions in Robotics, Int. J. Robotics Research, etc.
- B. Brogliato has been a reviewer for Automatica, Systems and Control Letters, Multibody System Dynamics, SIAM J. Control Optimization, IEEE Transactions Automatic Control, ASME Journal of Applied mechanics, European Journal of Mechanics A/Solids, Int. J. Robotics Research, etc.
- Organization of the summer school *Nonsmooth Contact Mechanics: Modeling and Simulation*, Aussois, 9-4 September 2012.
- V. Acary is co-animator (with R. Leine ETH Zurich) of the European network for nonsmooth dynamics. Member of the ENOC (EUROMECH Nonlinear Oscillations Conference) committee. Reviewer in 2012 for Math reviews, ASME Journal of Applied Mechanics, International Journal for Numerical Methods in Engineering, Journal of Franklin Institute, European Control Conference, American Control Conference, 51st IEEE Conference on Decision and Control (CDC 2012)

9.2. Teaching

Master : Bernard Brogliato, nonsmooth dynamical systems, 15h, M2, universit  de Limoges, France

Doctorat : Bernard Brogliato, Multiple Impacts, 7.5h, Aussois Ecole d' t  Inria Nonsmooth Contact Mechanics: Modeling and Simulation, France

Doctorat : Vincent Acary, Numerical simulation of nonsmooth mechanical systems, 9.5h, Aussois Ecole d' t  Inria Nonsmooth Contact Mechanics: Modeling and Simulation, France

Doctorat : Florence Descoubes, Numerical simulation of hair dynamics and fibers, 3.5h, Aussois Ecole d' t  Inria Nonsmooth Contact Mechanics: Modeling and Simulation, France

Master : F. Descoubes, Optimisation num rique, 30h equiv. TD, niveau M1, ENSIMAG, Grenoble INP

Master : J r me Malick, Optimisation num rique, 60h eqTD, Master1 of ENSIMAG

Master : P.-B. Wieber, Autonomous Robotics, 13.5h eqTD, Master2 Mosig

9.3. Supervision

PhD : Andrei Herdt, Model predictive control of a humanoid robot, Mines ParisTech, 27 Jan. 2012, Pierre-Brice Wieber and Bernard Espiau

PhD : Mehdi Benallegue, Mirror controller: A Bio-Inspired Computational Approach for Human Walking Motion Imitation by a Humanoid Robot, Universit  Montpellier 2, 15 Dec. 2011, Pierre-Brice Wieber and Bernard Espiau.

PhD : Zohaib Aftab, Dynamic Simulation of Balance Recovery: Application to the standing passengers of public transport, universit  de Lyon 1, 21 novembre 2012, Pierre-Brice Wieber and Thomas Robert and Bernard Brogliato

PhD in progress : Mounia Haddouni, 01 mai 2012, Vincent Acary et Bernard Brogliato

PhD in progress : Olivier Huber, 01 octobre 2011, Vincent Acary et Bernard Brogliato

PhD in progress : Narendra Akahdkar, 01 d cembre 2012, Vincent Acary et Bernard Brogliato

PhD in progress : Alexandre Derouet-Jourdan, 01 septembre 2010, Florence Descoubes et Joelle Thollot

PhD in progress : Sofia Zaourar, 01 octobre 2011, J r me Malick et Bernard Brogliato

PhD in progress : Romain Casati, 01 octobre 2011, Florence Descoubes et Bernard Brogliato

PhD in progress : Federico Pierucci, 01 octobre 2012, J r me Malick et Zaid Harchaoui et Anatoli Ioudilski

PhD in progress : Saed al Homsy, 01 octobre 2012, Pierre-Brice Wieber et Bernard Brogliato

PhD in progress : Jory Lafaye, 01 octobre 2012, Pierre-Brice Wieber et Bernard Brogliato

9.3.1. Popularization

- Two conferences on Robotics and Mathematics "Les robots, des puces plein la t te", for high-school students, and for high-school math teachers.

10. Bibliography

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Publications of the year

Articles in International Peer-Reviewed Journals

- [16] V. ACARY. *Higher order event capturing time-stepping schemes for nonsmooth multibody systems with unilateral constraints and impacts.*, in "Applied Numerical Mathematics", 2012, vol. 62, p. 1259-1275 [DOI : 10.1016/J.APNUM.2012.06.026], <http://hal.inria.fr/inria-00476398>.
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