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Activity Report 2014

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
Optimization and control of dynamic systems

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Project-Team BIPOP

Keywords: modeling, Simulation, Nonsmooth Analysis, Optimization, System Analysis And Control

Creation of the Project-Team: 2004 April 01.

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2. Overall Objectives

2.1. Overall Objectives

Generally speaking, this project deals with non-smooth systems, control, modelling and simulation, with emphasis on

- dynamic systems, mostly mechanical systems with unilateral constraints, impacts and set-valued friction models (liek Coulomb's friction), but also electrical circuits with ideal diodes and transistors Mos, sliding-mode controllers, biological neural networks, etc;
- numerical methods for nonsmooth optimization, and more generally the connection between continuous and combinatorial optimization.

3. Research Program

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

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

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: $0 \le y \perp \lambda \ge 0$ 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 $\langle \dot{x}(t) + F(x(t), t), v - x(t)\rangle \ge 0$ 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 [5], 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

optimization, numerical algorithm, convexity, Lagrangian relaxation, combinatorial 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 [11]) 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 [12].
- 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 [14].

4. Application Domains

4.1. 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.

4.2. 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 $1\mathrm{cm}^2$. It is out of the question to simulate a complete 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.

4.3. Walking robots

As compared to rolling robots, the walking ones – for example hexapods – possess definite advantages whenever the ground is not flat 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.

4.4. Optimization

Optimization exists in virtually all economic sectors. Simulation tools can be used to optimize the simulated system. 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 involved 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.

4.5. Computer graphics animation

Computer graphics animation is dedicated to the numerical modeling and simulation of physical phenomena featuring a high visual impact. Typically, deformable objects prone to strong deformation, large displacements, complex and nonlinear or even nonsmooth behavior, are of interest for this community. We are interested in two main mechanical phenomena: on the one hand, the behavior of slender (nonlinear) structures such as rods, plates and shells; on the other hand, the effect of frictional contact between rigid or deformable bodies. In both cases the goal is to design realistic, efficient, robust, and controllable computational models. Whereas the problem of collision detection has become a mature field those recent years, simulating the collision response (in particular frictional 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. 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. Finally, we are interested in studying certain discrepancies (inexistence of solution) due to the combination of incompatible models such as contacting rigid bodies subject to Coulomb friction.

5. New Software and Platforms

5.1. Nonsmooth dynamics: Siconos

Participants: Vincent Acary, Maurice Brémond, Olivier Huber, Franck Pérignon.

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, intercations, 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/MECHANICS. 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 a industrial CAD library (OpenCascade and pythonOCC) to deal with complex body geometries and to compute the contact locations and distances between B-Rep description and on Bullet for contact detection between meshes.

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

5.2. Simulation of fibrous materials subject to frictional contact

5.2.1. MECHE: Modeling Entangling within Contacting hair fibErs

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

The software MECHE was essentially developed during the MECHE ADT (2009-2011, research engineer: Gilles Daviet), 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 [9]). 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 (which we have started to build in Gilles Daviet's PhD thesis). The core of this software was transferred to L'Oréal in 2011, and to AGT Digital in early 2013, by Gilles Daviet and Florence Bertails-Descoubes. It was also used for generating a number of simulations supporting at least 4 of our research publications.

6. New Results

6.1. Highlights of the Year

- Bernard Brogliato: keynote speaker at ICDVC-2014, 4th International Conference on Dynamics, Vibration and Control, August 23-25, 2014 in Shanghai, China. http://www.icdvc2014.org/

6.2. Multiple impacts modelling

Participant: Bernard Brogliato.

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. The influence of the kinetic angles in the rocking block motion with friction is analysed as well, numerically. Extensive experimental works have been conducted by our colleague C. Liu at PKU on a disc-ball system. Results are in [32] [67], and in the monograph [16]. Multiple impacts have also been tackled through generalized kinematic models using the kinetic metric [20].

6.3. The contact complementarity problem

Participants: Bernard Brogliato, Florence Bertails-Descoubes, Alejandro Blumentals.

The contact linear complementarity problem is an set of equalities and complementarity conditions whose unknowns are the acceleration and the contact forces. It has been studied in a frictionless context with possibly singular mass matrix and redundant constraints in [21], using results on well-posedness of variational inequalities obtained earlier by the authors. This is also the topic of the first part of the Ph.D. thesis of Alejandro Blumentals where the frictional case is treated as a perturbation of the frictionless case. The contact LCP is directly related to the so-called Painlevé's paradox of contact mechanics. In collaboration with C. Liu (Beijing university PKU) some results habe been obtained from the analysis of a compliant model in the limit. It shows on the classical sliding rod system that the inconsistent mode yield to instantaneous transition to a sticking mode. This is quite coherent with previous results obtained by Le xuan Anh in 1991 on the Painlevé-Klein system (bilateral constraints with Coulomb friction). The results will appear in Multibody System Dynamics in 2015.

6.4. Discrete-time sliding mode control

Participants: Vincent Acary, Bernard Brogliato, Olivier Huber.

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 [41], [42], [43], [45], [61]. This work is part of the ANR project CHASLIM. Within the framework of CHASLIM we have performed many experimental validations on the electropneumatic setup of IRCCyN (Nantes), which nicely confirm our theoretical and numerical predictions: the implicit implementation of sliding mode control, drastically improves the input and output chattering behaviours. In particular the high frequency bang-bang controllers which are observed with explicit discretizations, are completely suppressed. The implicit discretization has been applied to the classical equivament-based-control SMC, and also to the twisting sliding-mode controller [43].

6.5. Lur'e set-valued dynamical systems

Participants: Bernard Brogliato, Christophe Prieur.

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 [62]. The results in [64] extend those in [63] with an accurate characterization of the maximal monotonicity of the central operator of these systems, which consists of a projection-like operator. Concrete and verifiable criteria are provided for the above classes (complementarity, relay systems). Results on state observers and output feedback control for classes of Lur'e systems (namely: Moreau's sweeping process of first and second order, and with prox-regular sets) are proposed in [29], [44], [34]. Therein the convexity is replaced by the far more general notion of prox-regularity, which destroys the monotonicity. The input to state stability of measure driven differential equations has been tackled in [22], where some results from [29] are adapted.

6.6. Simulation and stability of piecewise linear gene networks

Participants: Vincent Acary, Arnaud Tonnelier, Bernard Brogliato.

This work has been done in collaboration with the IBIS project team, it is reported in [19]. Gene regulatory networks control the response of living cells to changes in their environment. A class of piecewise-linear (PWL) models, which capture the switch-like interactions between genes by means of step functions, has been found useful for describing the dynamics of gene regulatory networks. The step functions lead to discontinuities in the right-hand side of the differential equations. This has motivated extensions of the PWL models based on differential inclusions and Filippov solutions, whose analysis requires sophisticated numerical tools. We present a method for the numerical analysis of one proposed extension, called Aizerman-Pyatnitskii (AP)-extension, by reformulating the PWL models as a mixed complementarity system (MCS). This allows the application of powerful methods developed for this class of nonsmooth dynamical systems, in particular those implemented in the Siconos platform. We also show that under a set of reasonable biological assumptions, putting constraints on the right-hand side of the PWL models, AP-extensions and classical Filippov (F)-extensions are equivalent. This means that the proposed numerical method is valid for a range of different solution concepts. We illustrate the practical interest of our approach through the numerical analysis of three well-known networks developed in the field of synthetic biology.

In addition, we have investigated oscillatory regimes in repressilator-type models with piecewise linear dynamics [30]. We derived exact analytical conditions for oscillations and showed that the relative location between the dissociation constants of the Hill functions and the ratio of kinetic parameters determines the possibility of oscillatory activities. We also computed analytically the probability of oscillations. Results suggest that a switch-like coupling behaviour, a time-scale separation and a repressilator-type architecture with an even number of elements facilitate the emergence of sustained oscillations in biological systems.

6.7. Numerical analysis and simulation of mechanical systems with constraints

6.7.1. Event-capturing schemes for nonsmooth mechanical systems

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 proposed self-adapting schemes by applying time–discontinuous Galerkin methods to the measure differential equation in [28]. 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 [58], the approach is algorithmically specified, improved and applied to nonlinear multi-contact examples with friction. It is compared to other numerical schemes and it is shown that the newly proposed integration scheme yields a unified behavior for the description of contact mechanical problems. Especially, we provide time-integration of the nonimpulsive dynamics with semi–explicit Runge–Kutta method previously developed for differential algebraic equations.

6.7.2. Numerical time–integration methods for event-detecting schemes.

Participants: Vincent Acary, Bernard Brogliato, Mounia Haddouni.

The CIFRE thesis of M. Haddouni concerns the numerical simulation of mechanical systems subject to holonomic bilateral constraints, unilateral constraints and impacts. This work is performed in collaboration with ANSYS and the main goal is to improve the numerical time–integration in the framework of event-detecting schemes. Between nonsmooth events, time integration amounts to numerically solving a differential algebraic equations (DAE) of index 3. We have compared dedicated solvers (Explicit RK schemes, Half-explicit schemes, generalizes α-schemes) that solve reduced index formulations of these systems. Since the drift of the constraints is crucial for the robustness of the simulation through the evaluation of the index sets of active contacts, we have proposed some recommendations on the use of the solvers of dedicated to index-2 DAE. A manuscript has been submitted to Multibody System Dynamics.

6.7.3. Multibody systems with clearances (dynamic backlash)

Participants: Vincent Acary, Bernard Brogliato, Narendra Akadkhar.

The PhD thesis of N. Akadkhar under contract with Schneider Electric concerns the numerical simulation of mechanical systems with unilateral constraints and friction, where the presence of clearances in imperfect joints plays a crucial role. A first work deals with four-bar planar mechanisms with clearances at the joints, which induce unilateral constraints and impacts, rendering the dynamics nonsmooth. The objective is to determine sets of parameters (clearance value, restitution coefficients, friction coefficients) such that the system's trajectories stay in a neighborhood of the ideal mechanism (*i.e.* without clearance) trajectories. The analysis is based on numerical simulations obtained with the projected Moreau-Jean time-stepping scheme. These results have been reported in [37]. It is planned to extend these simulations to frictional cases and to mechanisms of circuit breakers.

6.8. Inverse modeling with contact and friction

6.8.1. Inverse statics of plates and shells

Participants: Florence Bertails-Descoubes, Romain Casati, Gilles Daviet.

We have started to investigate the problem of interpreting an arbitrary 3D mesh as an equilibrium configuration of an elastic plate/shell, subject to gravity and frictional contact forces. We have first considered a simple nodal shell model accounting for stretch, shear and bending. For such a model, inverse statics formulates as an ill-posed minimization problem with a nonlinear objective and nonsmooth constraints. Our objective is to examine this problem in the case where the rest pose of the system is left as unknown, while material parameters (mass, stiffness) are assumed to be known (inverse design problem). In some specific cases (cloth modeling), we use a priori information such as locally low Gaussian curvature so as to help the retrieval of most natural solutions. We plan to submit our results to Siggraph 2015. Targeted applications include virtual garment modeling and parameter retrieval from 3D image-based capture.

6.9. Modeling of fibrous medium

6.9.1. Continuous modeling of fiber assemblies

Participants: Florence Bertails-Descoubes, Gilles Daviet.

Following the exploratory project funded by Persyval (2013-2014), we have started to model an assembly of long elastic fibers (such as hair) using a continuous approach (continuum mechanics equations coupled with a nonsmooth stress-strain law). Interactions between air and fibers can then be naturally accounted for, increasing the realism of some macroscopic features compared to our previous discrete elements model. This is still work in progress and we will make some of our results publicly available in 2015.

6.10. Threshold in spiking neural models

Participant: Arnaud Tonnelier.

We studied the threshold for spike initiation in two-dimensionnal spiking neural models. A threshold criterion that depends on both the membrane voltage and the recovery variable is proposed. This approach provides a simple and unified framework that accounts for numerous voltage threshold properties. Implications for neural modeling are also discussed [31].

6.11. Nonsmooth modes in chains of impact oscillators

Participants: Vincent Acary, Guillaume James, Franck Pérignon.

Chains of impact oscillators arise for example as finite-element models of thin oscillating mechanical structures (a string under tension or a clamped beam) contacting rigid obstacles. Nonlinear periodic waves are observed in experiments on such systems, but relatively little is known from a theoretical point of view on their existence and stability. In 2008, Gendelman and Manevitch have analyzed the existence and stability of nonlinear localized modes (breathers) for discrete linear chains with a single node undergoing rigid impacts. In this work, we introduce a numerical method allowing to compute branches of time-periodic solutions when an arbitrary number of nodes undergo rigid impacts without energy dissipation. For this purpose, we reformulate the search of periodic solutions as a boundary value problem incorporating unilateral constraints. We illustrate this numerical approach by computing different families of breathers and nonlinear normal modes. Our method is much more effective than a numerical continuation of periodic solutions based on compliant models, which requires to integrate stiff differential equations and lead to costly numerical continuation. These results have been communicated in two international conferences, ENOC 2014 [35] and 11th World Congress on Computational Mechanics [36].

6.12. Traveling waves in spatially discrete excitable media

Participants: José Eduardo Morales, Arnaud Tonnelier, Guillaume James.

The propagation of traveling waves in excitable media is a widespread phenomenon, with applications ranging from forest fires to electrical signals propagating along nerve fibers. The case of spatially discrete excitable models is notoriously difficult to analyze. In particular, for the discrete FitzHugh-Nagumo reaction-diffusion system, the existence of pulses for a general class of bistable nonlinearities has been proved only recently (Hupkes and Sandstede, 2010). The existence of pulses under more general types of interactions (e.g. elastic instead of diffusive) remains an open question, as well as traveling wave propagation in higher-dimensional systems. These problems will be tackled in the PhD thesis of J.-E. Morales (advisors A. Tonnelier and G. James), which started on November 2013. J.-E. Morales has started to analyze pulse propagation in the excitable Burridge-Knopoff (BK) model, which finds applications in the context of nonlinear friction. This model includes elastic interactions between particles, and an additional difficulty linked with nonsmoothness of the (multivalued) Coulomb friction law. Using an idealized piecewise linear friction force, we have studied the propagation of a pulse wave in the discrete BK model. Using asymptotic methods, we proved the existence of a pulse wave and derived quantitative results for travelling wave properties.

6.13. Nonlinear waves in granular chains

Participants: Guillaume James, Bernard Brogliato.

Granular chains made of aligned beads interacting by contact (e.g. Newton's cradle) are widely studied in the context of impact dynamics and acoustic metamaterials. When a large number of beads are present, their dynamics can be described by infinite-dimensional differential equations, which possess a limited smoothness when unilateral Hertzian contact interactions are considered. In this context, we have developed and analyzed new reduced-order models describing nonlinear wave propagation in such systems. In the work [25] (collaboration with D.Pelinovsky, McMaster Univ.), we analyze small amplitude slowly modulated compression waves in the limit when the exponent of the Hertz force is close to unity. From a multiple scale analysis, we derive a Korteweg-de Vries equation with logarithmic nonlinearity allowing to approximate wave profiles, in particular solitary wave solutions. In the work [50] (collaboration with Y. Starosvetsky, Technion IIT), we prove existence of spatially localized nonlinear modes (breathers) in the DpS equation, an amplitude equation describing small oscillations in Newton's cradle over long time scales. For Hertz force exponents close to unity, we show that breather envelopes are well approximated by a Gaussian solution of the logarithmic nonlinear Schrödinger equation. This result is generalized to traveling localized oscillations (traveling breathers) generated by an impact in Newton's cradle (G. James, article in preparation). The existence of breathers is also analyzed in granular metamaterials consisting of hollow beads with internal masses (G. James) in collaboration with L. Liu, A. Vainchtein (Pittsburgh Univ.) and P. Kevrekidis (UMass Amherst) - article in preparation. In addition the LZB model introduced in [15] has been extensively used to numerically investigate wave phenomena in chains of aligned balls (tapered, monodisperse, anti-tapered, stepped chains). Thorough comparisons with experimental results reported in the Granular Matter literature have been made. The results are reported in the monograph [16].

6.14. Robotics

6.14.1. Lexicographic Least-Squares solver

Participants: Pierre-Brice Wieber, Dimitar Dimitrov.

We have been working on Multi-Objective Least-Squares problems with inequality constraints for the last few years, focusing especially on the Lexicographic case. The focus this year has been on nonlinear problems, in collaboration with Adrien Escande from JRL, Tsukuba, Japan. Questions concerning the second-order approximation, using a Gauss-Newton approach or considering more precise second-order information, and questions concerning the globalization scheme, trust-region and/or filter methods have been approached, but results are still preliminary.

6.14.2. Mobile manipulation by humanoid robots

Participants: Pierre-Brice Wieber, Dimitar Dimitrov, Alexander Sherikov, Jory Lafaye.

The realization of mobile manipulation by humanoid robots requires the handling of two simultaneous problems: taking care of the dynamic balance of the robot, what is usually done with Model Predictive Control (MPC) schemes, and redundant motion and force control of the whole body of the robot, what is usually done with a Quadratic Program, or a more advanced Lexicographic Least-Squares problem (see above). These two problems are usually solved in sequence: an MPC scheme first computes the necessary motion of the feet and Center of Mass (CoM) of the robot, then motion and force redundancy of the whole body of the robot is resolved. We have observed that this sequence corresponds to a lexicographic order between two objectives, feet and CoM motion first, the rest of the body after, which limits the possibility to tackle scenarios where we would like the motion of the CoM of the robot to be driven by the motion of the rest of the body of the robot, for example to catch an object with the hand. We have proposed therefore to reorganize the order between these different objectives, building on the LexLS solver presented above. The focus this year has been on non-coplanar multi-contact situations.

6.14.3. Reactive trajectory generation

Participants: Pierre-Brice Wieber, Dimitar Dimitrov, Saed Al Homsy, Matthieu Guilbert.

The goal of the ongoing collaboration with Adept Technologies is to generate near time optimal trajectories in the presence of moving obstacles in real time. Results are not public yet due to industrial constraints.

6.15. Optimization

6.15.1. Semidefinite programming and combinatorial optimization

Participant: Jérôme Malick.

We have worked with Frederic Roupin (Prof. at Paris XIII) and Nathan Krislock (Assistant Prof. at North Illinois University, USA) on the use of semidefinite programming to solve combinatorial optimization problems to optimality.

We proposed a new family of semidefinite bounds for 0-1 quadratic problems with linear or quadratic constraints [65]. We have embedded the new bounds within branch-and-bound algorithms to solve 2 standard combinatorial optimization problems to optimality.

- *Max-cut.* We developed [26] 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 ([66]) on the large test-problems.
- *Heaviest k-subgraph problems*. Adapting the techniques we developped for the max-cut problem, we have proposed in [60] an algorithm 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).

We have also been working on a generic online semidefinite-based solver for binary quadratic problems using the generality of [65]. Finally, a first web interface for our solvers and our data sets are available online at http://lipn.univ-paris13.fr/BiqCrunch/.

6.15.2. Quadratic stabilization of Benders decomposition

Participants: Jérôme Malick, Sofia Zaourar.

The Benders decomposition, a fundamental method in operation research, is known to have the inherent instability of cutting plane-based methods. The PhD thesis of Sofia Zaourar proposes a algorithmic improvement of the method inspired from the level-bundle methods of nonsmooth optimisation. We illustrate the interest of the stabilization on two classical network problems: network design problems and hub location problems. We also prove that the stabilized Benders method have the same theoretical convergence properties as the usual Benders method. An article about this research was submitted this summer.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Schneider Electric (Cifre Ph.D. thesis of N. Akhadkar)
- Ansys France (Cifre Ph.D. thesis of M. Haddouni)
- Aldebaran (Cifre Ph.D. thesis of J. Lafaye)
- Adept Technologies (Cifre Ph.D. thesis of S. al Homsi)

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- CHASLIM Chattering Free Sliding Mode Control: ANR BLAN 2011 BS03 007 01 (octobre 2011–octobre 2015), coordinator B. Brogliato.
- SLOFADYBIO Slow-fast dynamics applied to the biosciences (january 2015 – december 2016), coordinateur: Mathieu Desroches (Inria Rocquencourt).

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

Florence Bertails-Descoubes was awarded in November 2014 an ERC starting grant to work on the parameter identification of slender structures subject to contact and friction. The grand will start in 2015 and will serve to fund 3 PhD students, 2 post-docs and 1 engineer on a total project duration of 5 years.

8.3. International Initiatives

8.3.1. Inria International Labs

Vincent Acary is on sabbatical at Santiago from September 2014 to August 2016.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Ryo Kikuuwe (Associate professor, Khushu University, Japan) from 01 September 2014 to 28 February 2015.
- Nathan Krislock (Associate professor, North Illinios University, USA) from 01 June to 10 July.

8.4.2. Visits to International Teams

8.4.2.1. Sabbatical programme

Acary Vincent

Institution: CMM Chili (Date : Sep 2014 - Aug 2016)

Institution: Inria Chile (Date: Sep 2014 - Aug 2015)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events selection

9.1.1.1. member of the conference program committee

- Florence Bertails-Descoubes: Siggraph 2014 IPC and Eurographics 2014 IPC.
- Pierre-Brice Wieber: 2014 IEEE-RAS International Conference on Humanoid Robots

9.1.1.2. reviewer

- Bernard Brogliato: IEEE Conference on Decision and Control 2014, Euromech ENOC 2014.
- Pierre-Brice Wieber: IEEE International Conference on Robotics and Automation, IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE-RAS International Conference on Humanoid Robots

9.1.2. Journal

9.1.2.1. member of the editorial board

- Pierre-Brice Wieber: associate editor IEEE Transactions on Robotics.
- Jérôme Malick: associate editor Journal of Global Optimization.

9.1.2.2. reviewer

- Bernard Brogliato: Automatica, Systems and Control Letters, IEEE Transactions on Automatic Control, SIAM J. Control Optimization, Multibody System Dynamics, ASME J. Applied Mechanics, Nonlinear Dynamics.
- Florence Bertails-Descoubes: Siggraph, Siggraph Asia, TOG, Eurographics.
- Pierre-Brice Wieber: International Journal of Robotics Research, Autonomous Robots, Automatica, IEEE Transactions on Control Systems Technology
- Vincent Acary: Automatica, Systems and Control Letters, IEEE Transactions on Automatic Control, Journal Sound and Vibrations, International Journal for Numerical Methods in Engineering, Nonlinear Analysis: Hybrid systems and project calls Fondecyt and NSERC

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence :

Master : Bernard Brogliato, Hybrid Dynamical Systems, 30 h., M2, Grenoble INP.

Master : Pierre-Brice Wieber, Autonomous Robotics, 9 h., M2, Grenoble INP.

Master : Florence Bertails-Descoubes, Numerical Optimization, 10.5 h., M1, ENSIMAG (Grenoble INP)

Master : Jérôme Malick, Numerical Optimization, 50 h., M1, ENSIMAG (Grenoble INP)

Master : Jérôme Malick, Mathematical Programming, 16 h., M2, UJF

Master : Vincent Acary, Nonsmooth Dynamical Systems, 9 h., M2, Université de Limoges

9.2.2. Supervision

- PhD in progress : Mounia Haddouni, 01 mai 2012, Vincent Acary and Bernard Brogliato
- PhD in progress : Olivier Huber, 01 octobre 2011, Vincent Acary and Bernard Brogliato
- PhD in progress : Narendra Akahdkar, 01 décembre 2012, Vincent Acary and Bernard Brogliato
- PhD : Sofia Zaourar, 04 November 2014, Jérôme Malick and Bernard Brogliato
- PhD in progress : Romain Casati, 01 octobre 2011, Florence Bertails-Descoubes and Bernard Brogliato
- PhD in progress : Alejandro Blumentals, 01 octobre 2013, Florence Bertails-Descoubes and Bernard Brogliato
- PhD in progress : Gilles Daviet, 01 octobre 2013, Florence Bertails-Descoubes and Bruno Raffin (LIG)
- PhD in progress : Federico Pierucci, 01 octobre 2012, Jérôme Malick and Zaid Harchaoui and Anatoli Ioudilski
- PhD in progress : Saed al Homsi, 01 octobre 2012, Pierre-Brice Wieber and Bernard Brogliato
- PhD in progress : Jory Lafaye, 01 octobre 2012, Pierre-Brice Wieber and Bernard Brogliato
- PhD in progress : Alexander Sherikov, 01 décembre 2012, Pierre-Brice Wieber and Bernard Brogliato
- PhD in progress : Nicolas Cazy, 01 octobre 2013, Pierre-Brice Wieber and François Chaumette
- PhD in progress : Jose Eduardo Morales Morales, *Travelling pulses in spatially discrete excitable media*, 15 november, 2013, Arnaud Tonnelier and Guillaume James

9.2.3. Juries

- Bernard Brogliato: Saed Aoues (04 décembre 2014), Laboratoire Ampère, INSA de Lyon (directeur de thèse D. Eberard). *Schémas d'intégration dédiés à l'étude, l'analyse et la synthèse dans le formalisme hamiltonien à ports*, Jury: D. Eberard, B. Maschke, T. Helie, E. Busvelle, A. Seuret, W. Marquis-Favre, B. Brogliato (Rapporteur).

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Major publications by the team in recent years

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Articles in International Peer-Reviewed Journals

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