IN PARTNERSHIP WITH:
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Institut polytechnique de Grenoble

Université Joseph Fourier (Grenoble)

Activity Report 2015

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

Table of contents

Project-Team BIPOP

Creation of the Project-Team: 2004 April 01

Keywords:

Computer Science and Digital Science:
5.10. - Robotics
5.10.4. - Robot control
5.10.5. - Robot interaction (with the environment, humans, other robots)
5.5. - Computer graphics
5.5.1. - Geometrical modeling
6. - Modeling, simulation and control
6.1.1. - Continuous Modeling (PDE, ODE)
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.3. - Observability and Controlability
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:
1.3.1. - Understanding and simulation of the brain and the nervous system
5. - Industry of the future
5.6. - Robotic systems
9.4. - Sciences
9.4.2. - Mathematics

1. Members

Research Scientists
Bernard Brogliato [Team leader, Inria, Senior Researcher, HdR]
Vincent Acary [Inria, Researcher, on leave at Inria Chili from Sep 2014 to August 2016, HdR]
Florence Bertails-Descoubes [Inria, Researcher]
Jerome Malick [CNRS, Researcher]
Arnaud Tonnelier [Inria, Researcher]
Pierre Brice Wieber [Inria, Researcher]

Faculty Member
Guillaume James [INP Grenoble, Professor, HdR]

Engineers
Camille Brasseur [Inria]
Dimitar Dimitrov [Inria, granted by OSEO Innovation]
Franck Perignon [CNRS]

PhD Students
Narendra Akhadkar [Schneider Electric, granted by CIFRE]
Alejandro Blumentals [Univ. Grenoble I]

Nestor Alonso Bohorquez Dorante [Inria, from Feb 2015]
Gilles Daviet [Univ. Grenoble I]
Olivier Huber [INP Grenoble, until May 2015]
Jory Lafaye [Aldebaran, until May 2015, granted by CIFRE]
Jose Eduardo Morales Morales [Inria]
Alexander Sherikov [Inria, granted by OSEO Innovation]
Alexandre Vieira [INP Grenoble, from September 2015]
Felix Miranda Villatoro [Internship from Cinvestav Mexico, from Sep 2015 to Feb 2016]
Romain Casati [INP Grenoble, Until June 2015]
Mounia Haddouni [ANSYS France, until May 2015, granted by CIFRE]
Sofia Michel [INP Grenoble, until Jun 2015]
Saed Alhomsi [ADEPT Technology, granted by CIFRE]

Visiting Scientists
Ryo Kikuuwe [Professor Kyushu University, until Mar 2015]
Nathan Krislock [Assistant Professor Iowa University, July 2015]

Administrative Assistant
Diane Courtiol [Inria]

Others
Alexandre Vieira [INSA de Rouen, student, April to September 2015]
Brice Portelenelle [ENSIMAG, student, from Feb 2015 until May 2015]
Cecile Rapoutet [Inria, student, from Jun 2015 until Aug 2015]
Liam Toran [ENS Lyon, student, from Jun 2015 until Jul 2015]
Christophe Prieur [DR2 CNRS GIPSA Lab, part-time external member since 2010]

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 (like 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

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

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. See [7], [8], [18] for a survey on models and control issues in nonsmooth mechanical systems.

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 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 [15].
- 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 [16].

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 [19], [20].

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 1cm^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 [1].

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. 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.

4.5. Multibody Systems: Modeling, Control, Waves, Simulation

Multibody systems are assemblies of rigid or flexible bodies, typically modeled with Newton-Euler or Lagrange dynamics, with bilateral and unilateral constraints, with or without tangential effects like friction. These systems are highly nonlinear and nonsmooth, and are therefore challenging for modeling aspects (impact dynamics, especially multiple –simultaneous– collisions), feedback control [10], state observation, as well as numerical analysis and simulation (software development) [2], [4], [5]. Biped robots are a particular, interesting subclass of multibody systems subject to various constraints. Granular materials are another important field, in which nonlinear waves transmissions are crucial (one celebrated example being Newton's cradle) [18], [13], [6], [14]. Fibers assemblies [11], circuit breakers, systems with clearances, are also studied in the team.

4.6. Stability and Feedback Control

Lyapunov stability of nonsmooth, complementarity dynamical systems is challenging, because of possible state jumps, and varying system's dimension (the system may live on lower-dimensional subspaces), which may induce instability if not incorporated in the analysis [8], [9], [7]. On the other hand, the nonsmoothness (or the set-valuedness) may be introduced through the feedback control, like for instance the well-known sliding-mode controllers or state observers. The time-discretisation of set-valued controllers is in turn of big interest [3]. The techniques we study originate from numerical analysis in Contact Mechanics (the Moreau-Jean time-stepping algorithm) and are shown to be very efficient for chattering suppression and Lyapunov finite-time stability.

5. New Software and Platforms

5.1. ACEF

- Participants: Vincent Acary and Olivier Bonnefon

5.2. Approche

- Participants: Alexandre Derouet-Jourdan, Florence Bertails-Descoubes and Joëlle Thollot
- Contact: Florence Bertails-Descoubes
- URL: Approche

5.3. CloC

- Participants: Florence Bertails-Descoubes and Romain Casati
- Partner: UJF
- Contact: Florence Bertails-Descoubes
- URL: Cloc

5.4. MECHE-COSM

5.4.1. 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 [11]). 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.

5.5. Platforms: SICONOS

5.5.1. Platform A : SICONOS

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

In the framework of the FP5 European project Siconos (2002-2006), Bipop was the leader of the Work Package 2 (WP2), dedicated to the numerical methods and the software design for nonsmooth dynamical systems. This has given rise to the platform SICONOS which is the main software development task in the team. 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/

6. New Results

6.1. The contact complementarity problem, and Painlevé paradoxes

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, using results on well-posedness of variational inequalities obtained earlier by the authors [26]. 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 [37]. 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 have been obtained from the analysis of a compliant model in the limit [34]. 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). With R. Kikuuwe from Kyushu University, we have also proposed a new formulation of the Baumgarte's stabilisation method, for unilateral constraints and Coulomb's friction , which sheds new light on Painlevé paradoxes as well [29].

6.2. Analysis of compliant nonlinear contact models

Participants: Bernard Brogliato, Guillaume James, Alexandre Vieira.

The master thesis of A. Vieira consisted of the study of suitable numerical method for compliant contact/impact models like the Simon-Hunt-Crossley and the Kuwabara-Kono models. These two models extend Hertz' contact by adding a dissipative force that takes the form of nonlinear viscous friction (nonlinear spring/dashpot). The fact that the Kuwabara-Kono dissipation is non-Lipschtiz requires particular care.

6.3. 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 [3]. 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 [22]. This work was 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, both for the classical order-one ECB-SMC and the twisting algorithms [33], [42], [27], [28]. 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 equivalent-based-control SMC, and also to the twisting sliding-mode controller. The case of a nonlinear controller is studied in [35].

6.4. Lur'e set-valued dynamical systems: State observers

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. We study in [53], [32] state observers for particular Lur'e systems which are Moreau's sweeping processes modelling Lagrange dynamics with frictionless unilateral constraints.

6.5. Measure Driven ODEs

Participants: Bernard Brogliato, Christophe Prieur.

Measure driven Ordinary differential equations are analyzed in [31] from the point of view of input-to-state stability (ISS). This relies on the solution concept introduced by Bressan and Rampazzo. Lyapunov-like functions are used to caracterize the ISS. The link with impulsive ODEs and switching systems is made.

6.6. Numerical analysis of multibody mechanical systems with constraints

This scientific theme concerns the numerical analysis of mechanical systems with bilateral and unilateral constraints, with or without friction [2]. They form a particular class of dynamical systems whose simulation requires the development of specific simulators.

6.6.1. 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.

6.6.2. 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 [47]. It is planned to extend these simulations to frictional cases and to mechanisms of circuit breakers.

6.7. Nonlinear waves in granular chains

Participants: Guillaume James, Bernard Brogliato, Alexandre Vieira.

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. While much effort has been devoted to the theoretical and experimental analysis of solitary waves in granular chains, there is now an increasing interest in the study of breathers (spatially localized oscillations) in granular systems. Due to their oscillatory nature and associated resonance phenomena, static or traveling breathers exhibit much more complex dynamical properties compared to solitary waves. Such properties have strong potential applications for the design of acoustic metamaterials allowing to efficiently damp or deviate shocks and vibrations. Our contribution to this field is twofold. In the work [52], the existence of static breathers is analyzed in granular metamaterials consisting of hollow beads with internal masses. Using multiple scale analysis and exploiting the unilateral character of Hertzian interactions, we show that long-lived breather solutions exist but time-periodic breathers do not (breather solutions actually disperse on long time scales). Moreover, in a collaboration with Y. Starosvetsky and D. Meimukhin (Technion), we numerically study the persistence of traveling breathers in granular chains with local potentials under the effect of contact damping. Using a viscoelastic damping model (Hertz-Kuwabara-Kono model), we show that breathers can be generated by simple impacts in granular chains made from various materials (breathers propagate over a significant number of sites before being damped). The design of an experimental setup to test these theoretical predictions is underway. Another series of works concerns more specifically the modeling and numerical analysis of dissipative impacts : introduction of appropriate variables and simplifications for different models of contact damping (James, Brogliato), and comparative tests for various numerical discretizations of the Hunt-Crossley and Kuwabara-Kono models (Vieira, Brogliato, James).

6.8. Traveling pulses in the Burridge-Knopoff model

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

The Burridge-Knopoff model describes the earthquake faulting process through the interaction of two plates modeled as a chain of blocks elastically coupled subject to a friction force. We study the existence of soliton-like solutions for the excitable Burridge-Knopoff model with different friction forces. We report for the first time the propagation of a one-pulse solitary wave where the position of the blocks remains unchanged after the passage of the wave. Extensive numerical simulations are done for different friction laws and a systematic investigation of the influence of the pulling velocity and the coupling constant is done. For a piecewise linear frictional law, we prove the existence of a traveling pulse in the weak coupling limit. A lower bound of the propagation speed is derived together with results on the shape of the traveling wave.

6.9. Propagation in space-discrete excitable systems

Participant: Arnaud Tonnelier.

We introduce a simplified model of excitable systems where the response of an isolated cell to an incoming signal is idealized by a fixed pulse-shape function. When the total activity of the cell reaches a given threshold a signal is sent to its N neighbors. We show that a chain of such excitable cells is able to propagate a set of simple traveling waves where the time interval between the firing of two successive cells remains constant. A comprehensive study is done for a transmission line with $N = 2$ and $N = 3$. It is shown that, depending on initial copnditions, the network may propagate traveling waves with different velocities. Some necessary conditions for multistationarity are derived for an arbitrary N.

6.10. Inverse modeling with contact and friction

6.10.1. Inverse statics of plates and shells with frictional contact

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

We pursued our work on the static inversion of thin elastic shells, in the presence of contact and friction with an external object. We have shown how to formulate draping as a local constrained minimization problem, and we have generalized the adjoint method to this constrained case. These new results are included in Romain Casati's PhD thesis, defended in June 2015, and will be part of a paper to be submitted in 2016.

6.11. Continnum modeling of granular materials

6.11.1. Continuum modeling of granular materials

Participants: Florence Bertails-Descoubes, Gilles Daviet.

We have proposed a new numerical framework for the continuous simulation of dilatable materials with pressure-dependent (Coulomb) yield stress, such as sand or cement. Relying upon convex optimization tools, we have shown that the continuous equations of motion coupled to the macroscopic nonsmooth Drucker-Prager rheology can be interpreted as the exact analogous of the solid frictional contact problem at the heart of Discrete Element Methods (DEM), extended to the tensorial space. Combined with a carefully chosen finite-element discretization, this new framework allowed us to avoid regularizing the continuum rheology while benefiting from the efficiency of nonsmooth optimization solvers, mainly leveraged by DEM methods so far. Our numerical results were successfully compared to analytic solutions on model problems, such as the silo discharge, and we retrieved qualitative flow features commonly observed in reported experiments of the literature. This work is currently under review at the Journal of Non Newtonian Fluid Mechanics, and a preliminary version is available as a research report [43]. Furthermore, we have recently extended the approach to account for flows with a varying density, leveraging the Material Point Method to discretize the Drucker Prager yield criterion without linearization. This work will be submitted to ACM SIGGRAPH in 2016.

6.12. Nonsmooth optimisation and applications

6.12.1. 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. Nathan was the guest of the team during 2 months (June/July).

We have worked on a generic semidefinite-based solver for solve binary quadratic optimization problems. Using the generality of the bounds proposed in [54]. Our article is in revision in ACM Transaction of Mathematical Software. Our solver and our data sets are available online at http://lipn.univ-paris13.fr/BiqCrunch/.

Specializing the method of the k-cluster problem, we have proposed in [51] 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).

6.12.2. Stochastic optimization for electricity production

Participant: Jérôme Malick.

Everyday, electricity generation companies submit a generation schedule to the grid operator for the coming day; computing an optimal schedule is called the unit-commitment problem. In collaboration with W. van Ackooij from EDF, we have proposed in [44] a two-stage formulation of unit-commitment to better include the impact of renewable energies. We present a primal-dual decomposition approach to tackle large-scale instances of these two-stage problems, wherein both the first and second stage problems are full unit-commitment problems. We provide an analysis of the theoretical properties of the algorithm, as well as computational experiments showing the interest of the approach for real-life large-scale unit-commitment instances.

6.13. Robotics

6.13.1. Mobile manipulation by humanoid robots

Participants: Pierre-Brice Wieber, Dimitar Dimitrov, Alexander Sherikov, Jory Lafaye, Camille Brasseur, Nestor Alonso Bohorquez Dorante.

This year's contributions to the field of mobile manipulation by humanoid robots have been three-fold: a lexicographic MPC approach to the decision of using optional contacts when necessary to maintain balance (and only when necessary), a robust MPC approach to online generation of dynamic walking motion on uneven ground such as stairs, and an analysis of the role of viability and capturability in collision prevention, using once again a lexicographic MPC approach.

6.13.2. Reactive trajectory generation

Participants: Pierre-Brice Wieber, Dimitar Dimitrov, Saed Al Homsi.

The goal of the collaboration with Adept Technologies is to generate time optimal trajectories in the presence of moving obstacles in real time. Three approaches with increasing computational complexity have been proposed and validated experimentally. The cheapest approach begins with a standard bang-bang control which is time-optimal in the absence of obstacles, and simply projected on dynamic limits imposed by collision avoidance. This leads to reasonable results where collisions are explicitly avoided, but time-optimality is lost in the process. A more complex approach introduces an MPC scheme minimizing a weighted L1-norm, which is tuned to generate a time-optimal behavior in the absence of obstacles. In the presence of obstacles, time-optimality is once again lost, however, results are much improved with respect to the previous approach. The final, and most complex approach, considers time-optimality as a lexicographic objective: a lexicographic MPC scheme is proposed, which achieves time-optimality in the presence of obstacles, with reasonable online computation time. This work has been submitted to ICRA 2016.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Schneider Electric : CIFRE PhD thesis of Narendra Akadkhar (end of contract 31/12/2015).
- ANSYS France : CIFRE PhD thesis of Mounia Haddouni (end of contract 01/05/2015).
- ADEPT Technology : CIFRE PhD thesis of Saed AlHomsi (end of contract 31/12/2015).
- Aldebaran : CIFRE PhD thesis of Jory Lafaye (end of contract 30/06/2015).

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Project eBacuss from the Persyval Labex, with C. Prieur (GIPSA Lab), B. Bidegarray (LJK Grenoble), L. Fesquet (TIMA Grenoble).

8.2. National Initiatives

8.2.1. 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).

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. GEM

Title: from GEometry to Motion, inverse modeling of complex mechanical structures

Programm: H2020

Type: ERC

Duration: September 2015 - September 2020

Coordinator: Inria

Inria contact: Florence Bertails-Descoubes

With the considerable advance of automatic image-based capture in Computer Vision and Computer Graphics these latest years, it becomes now affordable to acquire quickly and precisely the full 3D geometry of many mechanical objects featuring intricate shapes. Yet, while more and more geometrical data get collected and shared among the communities, there is currently very little study about how to infer the underlying mechanical properties of the captured objects merely from their geometrical configurations. The GEM challenge consists in developing a non-invasive method for inferring the mechanical properties of complex objects from a minimal set of geometrical poses, in order to predict their dynamics. In contrast to classical inverse reconstruction methods, my proposal is built upon the claim that 1/ the mere geometrical shape of physical objects reveals a lot about their underlying mechanical properties and 2/ this property can be fully leveraged for a wide range of objects featuring rich geometrical configurations, such as slender structures subject to frictional contact (e.g., folded cloth or twined filaments). To achieve this goal, we shall develop an original inverse modeling strategy based upon a/ the design of reduced and high-order discrete models for slender mechanical structures including rods, plates and shells, b/ a compact and well-posed mathematical formulation of our nonsmooth inverse problems, both in the static and dynamic cases, c/ the design of robust and efficient numerical tools for solving such complex problems, and d/ a thorough experimental validation of our methods relying on the most recent capturing tools. In addition to significant advances in fast image-based measurement of diverse mechanical materials stemming from physics, biology, or manufacturing, this research is expected in the long run to ease considerably the design of physically realistic virtual worlds, as well as to boost the creation of dynamic human doubles.

8.3.1.2. COMANOID

Title: Multi-contact Collaborative Humanoids in Aircraft Manufacturing

Programm: H2020

Duration: January 2015 - January 2019

Coordinator: CNRS (Lirmm)

Partners:

Airbus Groups (France)

Centre national de la recherche scientifique (France)

Deutsches Zentrum für Luft - und Raumfahrt Ev (Germany)

Universita Degli Studi di Roma Lapienza (Italy)

Inria contact: Francois Chaumette

COMANOID investigates the deployment of robotic solutions in well-identified Airbus airliner assembly operations that are laborious or tedious for human workers and for which access is impossible for wheeled or rail-ported robotic platforms. As a solution to these constraints a humanoid robot is proposed to achieve the described tasks in real-use cases provided by Airbus Group. At a first glance, a humanoid robotic solution appears extremely risky, since the operations to be conducted are in highly constrained aircraft cavities with non-uniform (cargo) structures. Furthermore, these tight spaces are to be shared with human workers. Recent developments, however, in multi-contact planning and control suggest that this is a much more plausible solution than current alternatives such as a manipulator mounted on multi-legged base. Indeed, if humanoid robots can efficiently exploit their surroundings in order to support themselves during motion and manipulation, they can ensure balance and stability, move in non-gaited (acyclic) ways through narrow passages, and also increase operational forces by creating closed-kinematic chains. Bipedal robots are well suited to narrow environments specifically because they are able to perform manipulation using only small support areas. Moreover, the stability benefits of multi-legged robots that have larger support areas are largely lost when the manipulator must be brought close, or even beyond, the support borders. COMANOID aims at assessing clearly how far the state-of-the-art stands from such novel technologies. In particular the project focuses on implementing a real-world humanoid robotics solution using the best of research and innovation. The main challenge will be to integrate current scientific and technological advances including multi-contact planning and control; advanced visual-haptic servoing; perception and localization; human-robot safety and the operational efficiency of cobotics solutions in airliner manufacturing.

8.4. International Initiatives

8.4.1. Inria International Labs

Vincent Acary is on leave at Inria Chile from September 2014 to August 2016.

8.4.2. Inria International Partners

8.4.2.1. Informal International Partners

We lead collaborations with several foreign colleagues:

- Prof. Ryo Kikuuwe from Kyushu University, Japan.
- Prof. C. Liu from Peking University (PKU), Beijing, China [34].
- Prof. Thorsten Schindler from Munich Technical University.
- Prof. Nathan Krislock from North Illinois University [51].
- Prof. Yuli Starosvetsky, Technion Israel Institute of Technology.

8.4.3. Participation In other International Programs

Y. Starosvetsky (Technion, PI) and G. James (Co-PI) have been awarded a grant from the Pazi Foundation (Israel) on a 4-years project (2015-19) entitled *Experimental, computational and analytical study of wave propagation in 1D and 2D granular crystals mounted on the non-uniform elastic foundation with spatially and temporarily varying properties*.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

8.5.1.1. Internships

- Professor Ryo Kikuuwe from Kyushu University (Japan) visited BIPOP from 01 September 2014 to 31 March 2016.
- Professor Nathan Krislock from North Illinois University visited BIPOP in June/July 2015.

8.5.2. Visits to International Teams

8.5.2.1. Sabbatical programme

Acary Vincent

Date: Sep 2014 - Aug 2016

Institution: CMM (Chile)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. General chair, scientific chair

G. James is chairing with C.Daraio (ETH Zürich) and A. Vakakis (Univ. Illinois) the forthcoming Euromech colloquium 580 *Strongly nonlinear dynamics and acoustics of granular metamaterials*, which will be organized by the BIPOP team at Inria in July 2016.

9.1.2. Scientific events selection

9.1.2.1. Chair of conference program committees

- Florence Bertails-Descoubes was Program Chair of the 2015 ACM/EG Symposium on Computer Animation, together with Stelian Coros (Carnegie Mellon University).

9.1.2.2. Member of the conference program committees

- Bernard Brogliato was Program Committee Member for the first IEEE International Conference on Event-based Control, Communication, and Signal Processing (EBCCSP 2015), June 17-19, 2015, Krakow, Poland

  (www.ebccsp2015.org).
- Bernard Brogliato was in the International Program Committee de 14th European Control Conference, Linz, Austria, July 15-17, 2015.
- Florence Bertails-Descoubes was in the Program Committee of ACM SIGGRAPH Asia 2015.
- Pierre-Brice Wieber was Associate Editor for the 2015 IEEE RAS Humanoids Conference.

9.1.3. Journal

9.1.3.1. Member of the editorial boards

- Pierre-Brice Wieber is Associate Editor for IEEE Transactions on Robotics.
- Bernard Brogliato is Associate Editor for Nonlinear Analysis: Hybrid Systems (starting January 2016).

9.1.3.2. Reviewer - Reviewing activities

- Bernard Brogliato is a reviewer for Automatica, IEEE Transactions on Automatic Control, ASME Journal of Applied Mechanics, Multibody System Dynamics, Nonlinear Analysis, Systems and Control Letters.
- Arnaud Tonnelier is a reviewer for Physical Review E, Nonlinear Analysis: Hybrid Systems, Journal of Physics A, International Journal of Bifurcation and Chaos, SIADS, Mathematical Biosciences and Engineering.
- Florence Bertails-Descoubes is a reviewer for ACM SIGGRAPH, ACM SIGGRAPH Asia, ACM Transactions on Graphics, IEEE Transactions of Vizualisation and Computer Graphics, Eurographics, Computer Graphics Forum.
- Jérome Malick is reviewer for SIAM Journal of Optimization, Computational Optimization and Applications, Set-Valued and Variational Mathematics

9.1.4. Invited talks

- Florence Bertails-Descoubes gave the following invited talks in 2015:
  - *"Geometry and mechanics of fibers: some numerical models"*, Mathematical Progress in Expressive Image Synthesis, Kyushu University (Fukuoka, Japon), September 2015.

- *"Geometry and mechanics of fibers: some numerical models"*, Rencontres DYSCO, organized in Treffort (Isère) by the interdisciplinary laboratory of physics (LIPhy), May 2015.
- *"Modélisation numérique de fibres en contact : application à la synthèse de chevelures réalistes"*, Collège de France, Paris (within the course series given in 2015 by M.-P. Cani), April 2015.

9.1.5. Research administration

- Arnaud Tonnelier is member of CNU 26 (2011-2015).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master 2015-2016: Pierre-Brice Wieber, Autonomous Robotics, 9h, M2, MOSIG (Grenoble INP)

Master 2015 : Jérôme Malick, Numerical Optimization, 50 h., M1, ENSIMAG (Grenoble INP)

Master 2015 : Jérôme Malick, Mathematical Programming, 16 h., M2, UJF

Master 2015-2016: Florence Bertails-Descoubes, IRL Module, 3 h., M1, ENSIMAG (Grenoble INP)

9.2.2. Supervision

HdR : Vincent Acary, université Grenoble-Alpes, July 2015.

PhD : Romain Casati, Quelques contributions à la modélisation numérique de structures élancées pour l'informatique graphique, université Grenoble-Alpes, June 2015, F. Bertails-Descoubes.

PhD : Olivier Huber, Commande par modes glissants en temps discret, université Grenoble-Alpes, B. Brogliato and V. Acary.

PhD : Mounia Haddouni, Algorithmes de résolution de la dynamique du contact avec impact et frottement, université Grenoble-Alpes, B. Brogliato and V. Acary.

PhD : Jory Lafaye, Control of movements and balance of a humanoid robot with omnidirectional wheels, université Grenoble-Alpes, P.B. Wieber.

PhD in progress : Narendra Akadkhar, Analysis of multibody systems with joint clearances, January 2013, université Grenoble-Alpes, to be defended in March 2016, B. Brogliato and V. Acary.

PhD in progress : Alejandro Blumentals, Analysis of rigid and deformable mechanical systems with frictional constraints, université Grenoble-Alpes, September 2013, B. Brogliato and F. Bertails-Descoubes.

PhD in progress : Jose Morales Morales, Soliton in the excitable Burridge-Knopoff model, université Grenoble-Alpes, September 2013, G. James and A. Tonnelier.

PhD in progress : Gilles Daviet, Macroscopic modeling of granular and fibrous materials, université Grenoble-Alpes, September 2014, F. Bertails-Descoubes and B. Raffin.

PhD in progress : A. Sherikov, Control of humanoid robots, Université Grenoble-Alpes, P.B. Wieber.

PhD in progress : Alexandre Vieira, Commande optimale de systèmes linéaires de complémentarité, université Grenoble-Alpes, B. Brogliato and C. Prieur.

PhD in progress : Nestor Bohorquez, Safe motion for humanoid robots in human environments, Université Grenoble-Alpes, P.B. Wieber.

PhD in progress : Federico Pierucci, nonsmooth optimization for machine learning , université Grenoble-Alpes, J. Malick and A. Ioudilski.

PhD in progress : Saed Al Homsi, Génération en ligne de trajectoires optimales en temps pour des robots industriels en environnements dynamiques, 17 March 2016, université Grenoble-Alpes, P.B. Wieber.

9.2.3. Juries

- Bernard Brogliato:
  - Habilitation (HDR) of Gang Zheng, November 2015, Inria Lille.
  - PhD thesis of P.O. Lamarre (LJK, Grenoble), September 2015.
- Pierre-Brice Wieber:
  - PhD thesis of J. Agravante (LIRMM, Montpellier), December 2015.

9.3. Popularization

- Florence Bertails-Descoubes co-authored the paper “Approcher des courbes par des hélices” in the journal Quadrature (making the cover of the journal), together with Alexandre Derouet-Jourdan, April 2015.
- Pierre-Brice Wieber gave a lecture on “The best way to walk for a robot” to 100 high-school students during the national Mathematics week, March 2015.

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