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Institut polytechnique de Grenoble

Activity Report 2016

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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Creation of the Project-Team: 2004 April 01

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1. Members

Research Scientists

Bernard Brogliato [Team leader, Inria, Senior Researcher, HDR]
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Florence Descoubes [Inria, Researcher]
Arnaud Tonnelier [Inria, Researcher]
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Faculty Member

Guillaume James [INP Grenoble, Professor, HDR]

Engineers

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Eric Madaule [Inria, from Nov 2016, granted by ERC (European Research Council Executive Agency)]
Jan Michalczyk [Inria, granted by OSEO Innovation]
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Post-Doctoral Fellows

Victor Romero Gramegna [Inria, from Feb 2016, granted by ERC (European Research Council Executive Agency)]
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Others

Narendra Akhadkar [Schneider Electric, CIFRE PhD student, until April 2016]
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Dimitar Dimitrov [Inria, Post-Doctoral Fellow, until May 2016]
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Felix Miranda Villatoro [Inria, PhD student Cinvestav Mexico, internship, until Feb 2016]
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Christophe Prieur [CNRS, Gipsa lab Grenoble, Senior Researcher, External member, HDR]

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

nonsmooth mechanical systems, impacts, friction, unilateral constraints, complementarity problems, 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

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

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

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

Thus, the 2nd and 3rd lines in (1) define the modes of the hybrid systems, as well as the conditions under which transitions occur from one mode to another. The 4th line defines how transitions are performed by the state x. There are several other formalisms which are quite related to complementarity. See [7], [8], [15] for a survey on models and control issues in nonsmooth mechanical systems.

3.2. Nonsmooth optimization

optimization, numerical algorPierre-Brice Wieber.ithm, 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.
- 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.

$\Longrightarrow$*The optimization scientific activity in BIPOP is no longer existing after Jérôme Malick left BIPOP to lead the DAO team in the Laboratoire Jean Kuntzman.*

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 [16], [17].

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. We have focussed in the past years on the simulation of heterogeneous objects such as granular or fibrous materials, both with a discrete element point of view [11], and, more recently, with a macroscopic (continuum) point of view [23]. 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) [15], [12], [6], [13]. 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 (previous Expert Engineer now at INRA).
- Contact: Vincent Acary.

5.2. Approche

KEYWORD: Geometric computing

- Participants: Alexandre Derouet-Jourdan, Florence Descoubes and Joelle Thollot
- Contact: Florence Descoubes
- URL: http://bipop.inrialpes.fr/~bertails/Papiers/floatingTangents3d.html

5.3. CloC

Super Space Clothoids in C
KEYWORD: Physical simulation
FUNCTIONAL DESCRIPTION

Reference software implementing the paper "Super Space Clothoids", R. Casati and F. Bertails-Descoubes, ACM Transactions on Graphics, 2013

- Participants: Florence Descoubes and Romain Casati
- Partner: UJF
- Contact: Florence Descoubes
- URL: http://bipop.inrialpes.fr/people/casati/publications/codes/ssc.html

5.4. MECHE-COSM

Modeling Entangled fiber with frictional Contact in Hair
KEYWORDS: Physical simulation - Frictional contact - Thin elastic rod
FUNCTIONAL DESCRIPTION

Implements super-helices [Bertails et al. 2006] coupled together by a hybrid algorithm for frictional contact [Daviet et al. 2011].

- Participants: Gilles Daviet, Florence Bertails Descoubes and Florent Cadoux
- Contact: Florence Descoubes

5.5. SALADYN MULTIBODY

- Participants: Vincent Acary and Olivier Bonnefon
- Contact: Vincent Acary

5.6. SICONOS

KEYWORDS: NSDS - MEMS - DCDC - SD - Collision - Friction - Mechanical multi-body systems
FUNCTIONAL DESCRIPTION

Siconos is an open-source scientific software primarily targeted at modeling and simulating nonsmooth dynamical systems in C++ and in Python: - Mechanical systems (rigid or solid) with unilateral contact and Coulomb friction and impact (nonsmooth mechanics, contact dynamics, multibody systems dynamics or granular materials). - Switched Electrical Circuit such as electrical circuits with ideal and piecewise linear components: power converter, rectifier, Phase-Locked Loop (PLL) or Analog-to-Digital converter. - Sliding mode control systems. - Biology (Gene regulatory network). Other applications are found in Systems and Control (hybrid systems, differential inclusions, optimal control with state constraints), Optimization (Complementarity systems and Variational inequalities), Fluid Mechanics, and Computer Graphics.

- Participants: Vincent Acary, Olivier Bonnefon, Maurice Bremond and Franck Perignon
- Contact: Bernard Brogliato
- URL: http://siconos.gforge.inria.fr

5.7. Platforms: SICONOS

5.7.1. 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. 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 [22]. 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 [27]. It relies on a particular limiting process of normal cones.

6.2. 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 [25]. 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 [26], [25], [39]. 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. Incidentally an error in a previous article is corrected in [19]. The previous results deal with disturbances which are matched and uniformly upperbounded. In [48], [49] they are extended to the case of parametric uncertainties, which are more difficult to handle because they may yield unmatched equivalent disturbances, and these disturbances are not uniformly upperbounded by a constant. Finally the results in [20] deal with the numerical analysis (and not the discrete-time control, which is a different problem) of Lagrangian systems with set-valued controllers. An implicit Euler method is used, and the convergence is shown.

6.3. Lur'e set-valued dynamical systems

Participants: Bernard Brogliato, Christophe Prieur, Alexandre Vieira.

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 [31] state observers for particular Lur'e systems which are Moreau's sweeping processes modelling Lagrange dynamics with frictionless unilateral constraints. The observers are themselves set-valued (first order sweeping process with measures), a complete analysis (existence of solutions, stability of the error system) is led. In [51], we extend previous results in the team and also more recently by Camlibel and Schumacher, to solve the problem of output regulation for evolution variational inequalities (in a convex analysis setting). In the PhD thesis of A. Vieira, we attack the problem of optimal control of linear complementarity systems. In the first part of this thesis, the case when the LCS is equivalent to an ODE with Lipschitz continuous right-hand side, is treated. Starting from first-order necessary conditions stated in a broad context by Clarke, we show that the Pontryagin's conditions are a mixed LCS, that yield so-called MPEC problems.

6.4. 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.

6.4.1. 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.

6.4.2. 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 [21]. It is planned to extend these simulations to frictional cases and to mechanisms of circuit breakers.

6.5. 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. 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. In the work [29], 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). In [28], we consider the effect of adding precompression to the above system and establish that the envelope of small ampliude oscillations is governed by a nonlinear Schrödinger equation. This allows us to show that, depending on the applied precompression, normal modes can become modulationally unstable and evolve towards traveling breathers. 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 work in progress concerns more specifically the modeling and numerical analysis of dissipative impacts (James, Brogliato). The methodology is based on the introduction of appropriate variables and simplifications for different models of contact damping. A postdoctoral fellow will work on this topic in the team, starting January 2017.

6.6. Travelling waves in a spring-block chain sliding down a slope

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

In this work we study the dynamics of an infinite chain of identical blocks sliding on a slope under the effet of gravity. Each block is coupled to its nearest neighbour through linear springs and is subjected to a nonlinear friction force. For a piecewise-linear spinodal friction law, a closed-form expression of front waves is derived. Pulse waves are obtained as the matching of two travelling fronts with identical wave speeds. Explicit formulas are obtained for the wavespeed and the wave form in the anti-continuum limit. The link with propagating phenomena in the Burridge-Knopoff model is briefly discussed. These results have been reported in [44].

6.7. Solitary waves in the excitable Burridge-Knopoff model

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

The Burridge-Knopoff model is a lattice differential equation describing a chain of blocks connected by springs and pulled over a surface. This model was originally introduced to investigate nonlinear effects arising in the dynamics of earthquake faults. One of the main ingredients of the model is a nonlinear velocity-dependent friction force between the blocks and the fixed surface. For some classes of non-monotonic friction forces, the system displays a large response to perturbations above a threshold, which is characteristic of excitable dynamics. Using extensive numerical simulations, we show that this response corresponds to the propagation of a solitary wave for a broad range of friction laws (smooth or nonsmooth) and parameter values. These solitary waves develop shock-like profiles at large coupling (a phenomenon connected with the existence of weak solutions in a formal continuum limit) and propagation failure occurs at low coupling. We introduce a simplified piecewise linear friction law (reminiscent of the McKean nonlinearity for excitable cells) which allows us to obtain analytical expression of solitary waves and study some of their qualitative properties, such as wavespeed and propagation failure. We propose a possible physical realization of this system as a chain of impulsively forced mechanical oscillators. In certain parameter regimes, non-monotonic friction forces can also give rise to bistability between the ground state and limit-cycle oscillations and allow for the propagation of fronts connecting these two stable states. These results have been reported in [45]. In addition, an existence theorem for solitary waves in the Burridge-Knopoff model is proved in the weak coupling limit and for a piecewise-linear friction force.

6.8. 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 described by a fixed pulse-shape function. When the total activity of the cell reaches a given threshold a signal is sent to its N nearest 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 signals with different velocities. Some necessary conditions for multistationarity are derived for an arbitrary N.

6.9. Direct and inverse modeling of thin elastic rods and shells

6.9.1. Experimental validation of the inverse statics of a thin elastic rod

Participants: Florence Bertails-Descoubes, Victor Romero.

In collaboration with Arnaud Lazarus (UPMC, Laboratoire Jean le Rond d'Alembert), we have built an experimental set-up to fabricate thin elastic rods and measure their deformation, with the aim to validate our full process for inverse static design. This work is still ongoing.

6.9.2. Strain-based modeling of inextensible and developable shells

Participants: Florence Bertails-Descoubes, Romain Casati, Alejandro Blumentals.

We have worked out the analagous of a super-helix element for modeling an inextensible and developable shell patch, using only two material curvatures. As for the super-helix model, the terms of the dynamics can be integrated formally, leading to a rich and efficient dynamical model [36]. How to connect different patches together is a topic for future work.

6.9.3. Inverse statics of plates and shells with frictional contact

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

We study the problem of cloth inverse design, relying on a nodal shell model for modeling garments. We have shown how to formulate draping as a local constrained minimization problem, and we have generalized the adjoint method to handle constrained cases, e.g., frictional contact between the garment and the body [43].

6.10. Continnum modeling of granular materials

6.10.1. 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, published at the Journal of Non Newtonian Fluid Mechanics [24], has been 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. We have also included the handling of anisotropic flow, as well as the coupling of the flow with rigid bodies. These extensions led to a publication at ACM SIGGRAPH 2016 [23].

6.11. Robust Model Predictive Control for biped walking motion generation

Participants: Pierre-Brice Wieber, Diana Serra, Alexander Sherikov, Dimitar Dimitrov.

One of the main sources of nonlinearity in the Newton and Euler equations of motion of biped walking robots lie in the vertical motion of the Center of Mass. We proposed last year an approach that considers this nonlinearity as an uncertainty, in what would else be a linear system. We proposed then to use a robust linear MPC approach accordingly. The use of a linear approach allows fast computations to generate walking motions online. This year, we further developed this approach, by adapting the bounds on the uncertainty at each iteration of a Newton scheme, when solving the original nonlinear problem [35]. By using a robust approach within a Newton scheme, every iteration can be ensured to satisfy all dynamic constraints, so that we can limit the number iterations depending on the available computing power and always obtain a feasible solution. We also developed this year an application of this MPC approach to cases of collaborative carrying of heavy objects with a human partner [32].

6.12. Lexicographic Model Predictive Control for collision avoidance in dynamic environments

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

Collision avoidance may not always be feasible in dynamic environments, when new obstacles can appear too late and move too fast with respect to the dynamic limitations of the system. A typical situation is with a biped robot walking in a compact and uncooperative crowd, with limited field of view. This year, we have investigated and compared 3 different relaxations of the collision avoidance constraint in this setting [33]. In the first case, collisions are accepted if the robot first comes to a stop, what corresponds to standard ISO norms for the safety of robots. In the second case, collisions are actively minimised by the robot, what gives significantly better results. In the third case, for the sake of completeness, the robot is allowed to fall in order to further avoid collisions. All three options were implemented with different formulations of lexicographic relaxation of the constraints in a standard MPC scheme for biped walking motion generation. This work raises important issues regarding safety norms for robots in human environments and how they are implemented.

6.13. Lexicographic Programming

Participants: Pierre-Brice Wieber, Alexander Sherikov, Dimitar Dimitrov, Adrien Escande.

Lexicographic Programming has proved to be a very valuable tool in the last few years for relaxing selectively various constraints and objectives in the control of complex systems such as biped humanoid robots. A major difficulty however is that solutions to such problems very often lie at singular points, making the convergence of standard Newton schemes difficult. We have shown this year how a trust region with filter method can help improve convergence, at least in simple situations [40].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- CIFRE PhD thesis (N. Akhadkar) with Schneider Electric.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- 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

8.2.1.1. GEM

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

Programm: H2020

Type: ERC

Duration: September 2015 - August 2020

Coordinator: Inria

Inria contact: Florence BERTAILS

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.

8.2.1.2. COMANOID

Title: Multi-contact Collaborative Humanoids in Aircraft Manufacturing

Programm: H2020

Duration: January 2015 - December 2018

Coordinator: CNRS (Lirmm)

Partners:

Centre national de la recherche scientifique (France)

Deutsches Zentrum für Luft - und Raumfahrt Ev (Germany)

Airbus Groups (France)

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.

8.3. International Research Visitors

8.3.1. Visits to International Teams

8.3.1.1. Sabbatical programme

- Vincent Acary, Inria Chile from September 2014 to August 2016.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Guillaume James, Chairman of the Euromech Colloquium 580 “Strongly Nonlinear Dynamics and Acoustics of Granular Metamaterials”, 11 July-13 July 2016, Grenoble. http://580.euromech.org/

9.1.1.2. Member of the Organizing Committees

- Gilles Daviet, Alexandre Vieira, Jose Morales, Bernard Brogliato, members of local organization committee of the Euromech Colloquium 580 “Strongly Nonlinear Dynamics and Acoustics of Granular Metamaterials”, 11 July-13 July 2016, Grenoble. http://580.euromech.org/.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- Vincent Acary, member of ENOC (European Nonlinear Oscillations Conference) Committee.
- Florence Bertails-Descoubes, member of the ACM SIGGRAPH Asia 2016 Technical Program Committee.
- Pierre-Brice Wieber, Associate Editor for Humanoids 2016 and ICRA 2017.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Bernard Brogliato, Associate Editor at Nonlinear Analysis: Hybrid Systems
- Bernard Brogliato, Associate Editor at ASME Journal of Computational and Nonlinear Dynamics
- Pierre-Brice Wieber, Associate Editor at IEEE Transactions on Robotics

9.1.3.2. Reviewer - Reviewing Activities

- Bernard Brogliato, reviewer for IEEE Transactions on Automatic Control, Multibody System Dynamics, SIAM Journal on Optimization and Control, European Journal of Mechanics A/Solids, Nonlinear Dynamics, ASME Journal of Computational and Nonlinear Dynamics.
- Florence Bertails-Descoubes, reviewer for ACM Transactions on Graphics, ACM SIGGRAPH, ACM SIGGRAPH Asia, Eurographics, Symposium on Computer Animation, Computer-Aided Design, Computer-Aided Geometric Design, International Journal of Solids and Structures.
- Arnaud Tonnelier, reviewer for Scientific Reports, SIADS, PRE, PhysicaD.
- Vincent Acary, reviewer for several journals in Mechanics and Automatic Control.

9.1.4. Invited Talks

- Bernard Brogliato, invited seminar at Mathematics Department, INSA de Lyon, 09 June 2016 (contact: A. Petrov).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master 1 : Florence Bertails-Descoubes, Module IRL (découverte recherche), supervision stage Mickaël Ly, ENSIMAG 2A (Grenoble INP)

9.2.2. Supervision

HdR : Vincent Acary, Analysis, simulation and control of nonsmooth dynamical systems, Université de Grenoble Alpes, 16 juillet 2015.

PhD : Narendra Akhadkar, Modélisation numérique des mécanismes. Influence des jeux, de la déformation et des impacts multiples, Université Grenoble-Alpes, CIFRE I-MEP2 avec Schneider-Electric, 25 avril 2016, Vincent Acary et Bernard Brogliato

PhD : Gilles Daviet, Modèles et Algorithmes pour la Simulation du Contact Frottant dans les Matériaux Complexes : Application aux Milieux Fibreux et Granulaires, Universite’ Grenoble-Alpes, 15 décembre 2016, Florence Bertails-Descoubes.

PhD : José Eduardo Morales Morales, Ondes localisées dans des systèmes mécaniques discrets excitables, Universite’ Grenoble-Alpes, 29 novembre 2016, Guillaume James et Arnaud Tonnelier

PhD in progress : Alexandre Vieira, Commande Optimale de Systèmes Linéaires de Complémentarité, 01 octobre 2015, Christophe Prieur et Bernard Brogliato.s/'e

PhD in progress : Alejandro Blumentals, Analyse et Simulation de Systèmes Mécaniques avec Contact Frottant, 01 octobre 2013, Florence Bertails-Descoubes et Bernard Brogliato.

PhD in progress: Nestor Bohorquez Dorante, Control of Biped Robots, 01 octobre 2015, Pierre-Brice Wieber.

PhD in progress: Nahuel Vila, Control of Biped Robots, 01 octobre 2016, Pierre-Brice Wieber.

9.2.3. Juries

- Bernard Brogliato, member of Habilitation à Diriger des Recherches committee of Constantin Irinel Morarescu, CRAN Nancy (MCF université de Nancy), 03 novembre 2016.
- Bernard Brogliato, member of Habilitation à Diriger des Recherches committee of Stéphane Redon, Inria Grenoble (CR Inria), 27 mai 2016.
- Bernard Brogliato, member of Ph.D. Thesis committee of T.L. Nguyen (15 janvier 2016), INSA de Rennes (directeurs de thèse M. Hjiaj and C. Sansour).
- Bernard Brogliato, member of Ph.D. Thesis committee of O. Montano (20 mai 2016), CICESE Ensenada, Mexico (directeur de thèse Y. Orlov).
- Arnaud Tonnelier, member of Ph.D. Thesis committee of Catalina Vich Llompart (août 2016), Universitat de les Illes Balears (directeurs de thèse : Antoni Guillamon Grabolosa (UPC) and Dr. Prohens Rafel Sastre (UIB)).
- Arnaud Tonnelier, member of Ph.D. Thesis committee of Elif Köksal Ersöz (décembre 2016), Université Pierre et Marie Curie (directeurs de thèse: F. Clement et J.P. Françoise).

9.3. Popularization

- Modélisation de matériaux granulaires (Florence Bertails-Descoubes, Gilles Daviet) : participation à l'écriture d'un article court pour le CNRS, "Représenter du sable sans poudre aux yeux", http://www.cnrs.fr/ins2i/spip.php?article2175

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[2] V. Acary, B. Brogliato. *Numerical Methods for Nonsmooth Dynamical Systems: Applications in Mechanics and Electronics*, Lecture Notes in Applied and Computational Mechanics, Springer Verlag, 2008, vol. 35

[3] V. Acary, B. Brogliato. *Implicit Euler numerical scheme and chattering-free implementation of sliding mode systems*, in "Systems and Control Letters", 2010, vol. 59, pp. 284-293

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