informatics mathematics

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

Activity Report 2017

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, end of the Project-Team: 2017 December 31

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1. Personnel

Research Scientists

Bernard Brogliato [Team leader, Inria, Senior Researcher, HDR]
Vincent Acary [Inria, Researcher, HDR]
Florence Bertails-Descoubes [Inria, Researcher, until Sep 2017 - created her Inria team ELAN in October 2017, HDR]
Arnaud Tonnelier [Inria, Researcher]
Pierre Brice Wieber [Inria, Researcher]

Faculty Member

Guillaume James [Institut polytechnique de Grenoble, Professor, HDR]

Post-Doctoral Fellows

Victor Romero Gramegna [Inria, until Jan 2017]
Kirill Vorotnikov [Inria]

PhD Students

Alejandro Blumentals [Inria, until Jun 2017]
Nestor Alonso Bohorquez Dorante [Inria]
Alexandre Vieira [Institut polytechnique de Grenoble]

Nahuel Villa [Inria]

Technical staff

Alejandro Blumentals [Inria, from Sep 2017 until Nov 2017, granted by FP7 H ICT- / COMANOID project]
Stanislas Brossette [Inria, from Feb 2017]
Eric Madaule [Inria, until Sep 2017]
Jan Michalczyk [Inria, granted by FP7 H ICT- / COMANOID project]
Nicolas Pautet [Inria, until Sep 2017]
Franck Perignon [CNRS]
Victor Romero Gramegna [Inria, from Feb 2017 until Sep 2017]
Alexander Sherikov [Inria, until Sep 2017, granted by OSEO Innovation]

Interns

Abdulhadi Saad Ramadan Abdlgwad [Inria, from Oct 2017]
Raphael Charrondiere [Ecole Normale Supérieure Lyon, Sep 2017]
Gabriel Devillers [Univ Grenoble Alpes, until Apr 2017]
Wafae Hatifi [Inria, from Nov 2017]
Hamza Jaffali [Inria, from Feb 2017 until Jul 2017]
Cesare Molinari [Inria, until Feb 2017]
Carlos Yoong [Inria, until Mar 2017]

Administrative Assistant

Diane Courtiol [Inria]

Visiting Scientists

Alexandre Derouet-Jourdan [OLM Digital, Japan, from Aug 2017 until Oct 2017]
Jozsef Kovecses [McGill University, Montreal, Quebec, Canada, Oct 2017]
Dario Mangoni [Universita di Parma, Italy, from May 2017 until Jun 2017]
Christophe Prieur [CNRS, Senior Researcher, 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.

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

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

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], [17] for a survey on models and control issues in nonsmooth mechanical systems.

3.2. Nonsmooth optimization

optimization, numerical algorithms.

$\Longrightarrow$*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 [18], [19].

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 [12]. 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) [17], [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. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Gilles Daviet has been awarded the 2017 PhD award of the national GdR IG-RV, http://www.af-rv.fr/blog/2017/07/10/resultats-du-prix-de-these-du-gdr-ig-rv-2017/, for his PhD thesis entitled 'Modèles et algorithmes pour la simulation du contact frottant dans les matériaux complexes, application aux milieux fibreux et granulaires'.

6. New Software and Platforms

6.1. ACEF

Automatic switched Circtuits Equation Formualtion
KEYWORDS: Simulation - Electrical circuit - Switched systems
SCIENTIFIC DESCRIPTION: Nonsmooth Modeling and Simulation for Switched Circuits concerns the modeling and the numerical simulation of switched circuits with the nonsmooth dynamical systems (NSDS) approach, using piecewise-linear and multivalued models of electronic devices like diodes, transistors, switches. Numerous examples (ranging from introductory academic circuits to various types of power converters) are analyzed and many simulation results obtained with the Inria open-source SICONOS software package are presented. Comparisons with SPICE and hybrid methods demonstrate the power of the NSDS approach. Nonsmooth Modeling and Simulation for Switched Circuits is intended to researchers and engineers in the field of circuits simulation and design, but may also attract applied mathematicians interested by the numerical analysis for nonsmooth dynamical systems, as well as researchers from Systems and Control.

References: Nonsmooth Modeling and Simulation for Switched Circuits Authors: Acary, Vincent, Bonnefon, Olivier, Brogliato, Bernard (http://www.springer.com/fr/book/9789048196807)
FUNCTIONAL DESCRIPTION: The Automatic Circuit Equations Formulation (ACEF) module is the implementation of the automatic circuit equation extended to general nonsmooth components. From a SPICE netlist, possibly augmented by some nonsmooth components, the ACEF builds a dynamical formulation that can be simulated by SICONOS.

- Participants: Olivier Bonnefon and Vincent Acary
- Contact: Vincent Acary
- URL: http://bipop.inrialpes.fr/people/acary/

6.2. Approche

KEYWORD: Geometric computing

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

6.3. 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

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

6.5. N1cv2

KEYWORDS: Optimization - Decomposition

- Participants: Claude Lemaréchal and Claudia Sagastizabal
- Partners: Université fédérale de Rio de Janeiro - Université de Varsovie - Université de Washington - Université de Pise
- Contact: Jérôme Malick
- URL: http://www.inrialpes.fr/bipop/

6.6. SALADYN MULTIBODY

KEYWORDS: Physical simulation - Co-simulation
FUNCTIONAL DESCRIPTION: The project SALADYN aims at designing and implementing a new software platform into Salomé-Méca by coupling three kinds of mechanical models: a) Deformable bodies, mainly through their finite element representation, b) rigid multi-body systems and c) multi-contact systems. The goal is to obtain a close coupling of these models for the modeling and the simulation in a nonsmooth dynamical framework, able to deal rigorously with the unilateral contact and Coulomb's friction. This platform will be composed by the integration of the following components:

Salomé. An OpenSource platform for the pre and post-processing and the coupling of numerical software codes. Code_Aster. An OpenSource Finite Element Application, which has already been integrated in Salomé, under the name of Salomé-méca. LMGC90. An OpenSource software for the modeling and the simulation of multicontact systems. Siconos. An OpenSource software for the modeling, the simulation and the control of nonsmooth Dynamical systems Besides this integration, the main deliverable of this project is a common numerical software which allows the interoperability of the models trough a multiple representation of an unique physical object, and a dynamic adaptability in time based on the user needs and the simulation requirements (accuracy, efficiency, abstraction, etc.). The consortium (Schneider Electric, EDF, Inria, LMGC, LAMSID) brings together well-recognized skills of academic laboratories and companies, which possess a strong experience in structural analysis and dynamical analysis in the field of nonsmooth dynamics. The industrial partners will provide the project with effective test-beds and experiments, which will be very reliable element for validation and performance analysis. The expected result of this project should concern a large field of application ranging from transport, energy, micro-mechanical systems to divided materials such as Masonry or granular matter.

More generally, one aim of this project is to federate the national academic and industrial community for the design and the simulation of complex mechanical in non smooth interactions into a common OpenSource software platform.

- Participants: Olivier Bonnefon and Vincent Acary
- Contact: Vincent Acary
- URL: http://saladyn.gforge.inria.fr

6.7. SICONOS

Modeling, simulation and control of nonsmooth dynamical systems
KEYWORDS: Friction - Collision - SD - DCDC - MEMS - NSDS - 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: Franck Pérignon, Maurice Bremond, Olivier Bonnefon and Vincent Acary
- Contact: Vincent Acary
- URL: http://siconos.gforge.inria.fr

6.8. Platforms: SICONOS

6.8.1. 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/

7. New Results

7.1. 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. 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 [24]. It relies on a particular limiting process of normal cones.

7.2. Discrete-time sliding mode control

Participants: Vincent Acary, Bernard Brogliato.

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. 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. 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 [48]. The previous results deal with disturbances which are matched and uniformly upperbounded. In [26] the SMC of Lagrange systems is studied. In [35] this is 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. A nested controller is proposed in [36], using a backstepping-like approach for the controller synthesis.

7.3. Linear Complementarity Systems

Participants: Bernard Brogliato, Christophe Prieur, Alexandre Vieira.

The quadratic optimal control of Linear complementarity systems (LCS) is analysed in [37]. The major difficulty comes from the fact that complementarity conditions introduce non convex constraints. Suitable algorithms have to be used to solve the MPEC problems for solving the direct method. The indirect (Pontryagin's) approach is quite delicate and is currently analysed in the PhD thesis of A. Vieira.

7.4. 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.

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

Participants: Vincent Acary, Bernard Brogliato.

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. The results are reported in [23].

7.4.2. Multibody systems with clearances (dynamic backlash)

Participants: Vincent Acary, Bernard Brogliato.

The PhD thesis of N. Akadkhar under contract with Schneider Electric has concerned 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. Circuits breakers with 3D joint clearances have been studied in [20], [31] where it is demonstrated that the nonsmooth dynamics approach as coded in our software SICONOS, allows a very good prediction of the system's dynamics, with experimental validation. An overview of various approaches for the feedback control of multibody systems with joint clearances is proposed in [21].

7.5. Nonlinear waves in dissipative granular chains

Participants: Guillaume James, Bernard Brogliato, Kirill Vorotnikov.

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. In order to describe the response of such systems to impacts or vibrations, it is important to analyze different wave effects such as the propagation of localized compression pulses (solitary waves) or the scattering of vibrations through the chain. Such phenomena are strongly influenced by contact nonlinearities (Hertz force), spatial inhomogeneities and dissipation. In this work, we analyze the Kuwabara-Kono (KK) model for contact damping, and we develop new approximations of this model which are efficient for the simulation of multiple impacts. The KK model is a simplified viscoelastic contact model derived from continuum mechanics, which allows for simpler calibration (using material parameters instead of phenomenological ones), but its numerical simulation requires a careful treatment due to its non-Lipschitzian character. Using different dissipative time-discretizations of the conservative Hertz model, we show that numerical dissipation can be tuned properly in order to reproduce the physical dissipation of the KK model and associated wave effects. This result is obtained analytically in the limit of small time steps (using methods from backward analysis) and is numerically validated for larger time steps. The resulting schemes turn out to provide good approximations of impact propagation even for relatively large time steps.

7.6. Periodic motions of coupled impact oscillators

Participants: Guillaume James, Vincent Acary, Franck Pérignon.

In the work [40], we study the existence and stability of time-periodic oscillations in an infinite chain of linearly coupled impact oscillators, for rigid impacts without energy dissipation. We reformulate the search of periodic solutions as a boundary value problem incorporating unilateral constraints. This formulation, together with an appropriate notion of nondegenerate modes, allows us to construct nonsmooth modes of oscillations (spatially localized or extended) when the oscillators are weakly coupled (this approach is an adaptation of the idea of "anticontinuum" limit to the nonsmooth setting). In this framework, we show the existence of exact solutions (in particular, we check the condition of non-penetration of the obstacle) for an arbitrary number of impacting particles. Different solution branches corresponding to stable or unstable breathers, multibreathers and nonsmooth normal modes are found. We provide a formula for the monodromy matrix that determines spectral stability of nonsmooth modes in the presence of simple impacts. These results are completed by a numerical computation of the time-periodic solutions at larger coupling, and the Siconos software is used to simulate the system and explore dynamical instabilities. The above approach is much more effective than numerical continuation of periodic solutions based on stiff compliant models, which leads to stiff ODEs and costly numerical continuation.

7.7. Stability analysis for rogue waves

Participant: Guillaume James.

The study of rogue waves (large amplitude waves localized both in space and time) has gained importance in various fields, such as the mathematical modeling of water waves and nonlinear optics. The analysis of their stability is delicate because of their transient nature. In the work [46], we introduce a new method to tackle this problem. Our approach relies on the approximation of rogue waves by large amplitude breathers (localized in space and time-periodic) having a large period, and the use of Floquet theory to analyze breather stability. This problem is examined for the nonlinear Schrödinger equation, which describes the envelope of nonlinear waves in a large class of systems, for example granular chains [15]. This model admits a family of breather solutions (Kuznetsov-Ma breathers) which converge to a rogue-wave profile (Peregrine soliton) when their period tends to infinity. We show numerically that the Floquet exponents of the breathers approach a finite limit for large periods, and observe that a motion of the localized wave can be induced by a dynamical instability. This work suggests an analytical way to define the spectral stability of the (transient) Peregrine soliton, but this remains an open problem to prove analytically the convergence of Floquet exponents in the limit of infinite period.

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

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

Spatially discrete systems (lattice differential equations) have a wide range of applications in natural sciences, engineering and social sciences. They frequently occur in physics as mass-spring systems with nearest-neighbors coupling and they have been used extensively to describe the dynamics of microscopic structures such as crystals or micromechanical systems, or to model fragmentation phenomena.
In this work, we consider a spring-block system that slides down a slope due to gravity. Each block is subjected to a nonlinear friction force. This system differs from the Burridge-Knopoff model considered for the modeling of earthquakes, which incorporates local potentials. We perform numerical simulations of the coupled system and show that the bistability property induces traveling patterns, as fronts and pulses. 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 published in [27].

7.9. 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. 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. These results have been reported in [28].
We have obtained an existence theorem for solitary waves in the Burridge-Knopoff model. Our approach uses a piecewise-linear friction force combined with a weak coupling strength. Using asymptotic arguments, we show that trial solutions, obtained semi-analytically, satisfy, for some parameter set, the inequality constraints associated with the threshold conditions. An approximation of the wave profile is obtained and a minimal wave speed is derived.

7.10. Propagation in space-discrete excitable systems

Participant: Arnaud Tonnelier.

We introduce a simplified model of excitable media where the response of an isolated element to an incoming signal is given by a fixed pulse-shape function. When the total activity of one element reaches a given threshold, a signal is sent to its N nearest neighbors. We show that an excitable chain supports the propagation of a set of simple traveling waves where the interval between the emitting time of two successive elements remains constant. We propose a classification of travelling waves that depends on the number of signals that are received by an element. Results on stability of travelling signals are derived. We also discussed the global shape of the speed curve (velocity of the wave with respect to the global coupling strength). In particular, we show that for a given network connectivity, different wave velocities can be obtained, i.e., depending on initial conditions, the network may propagate different signals. A comprehensive study is done for a transmission line with $N = 2$ and $N = 3$. Some necessary conditions for multistationarity are derived for an arbitrary N and for different network connectivities.

7.11. Inverse design of a suspended elastic rod

Participants: Florence Bertails-Descoubes, Victor Romero.

In collaboration with Alexandre Derouet-Jourdan (OLM Digital, Japan) and Arnaud Lazarus (UPMC, Laboratoire Jean le Rond d'Alembert), we have investigated the inverse design problem of a suspended elastic subject to gravity. We have proved that given an arbitrary space curve, there exists a unique solution for the natural configuration of the rod, which is independent of the initial framing of the input curve. Moreover, this natural configuration can be easily computed by solving three linear ODEs in sequence, starting from any input framing. This work has just been submitted for publication in physics.

7.12. Simulation of cloth contact with exact Coulomb friction

Participant: Florence Bertails-Descoubes.

In collaboration with Gilles Daviet (Weta Digital, New Zealand), Rahul Narain and Jie Lie (University of Minnesota), we have developed a new implicit solver for taking into account contact in cloth with Coulomb friction. Our key idea stems from the observation that for a nodal system like cloth, and in the case where each node is subject to at most one contacting constraint (either an external or self-contact), the frictional contact problem may be formulated based on velocities as primary variables, without having to compute the costly Delassus operator; then, by reversing the roles classically played by the velocities and the contact impulses, conical complementarity solvers of the literature may be leveraged to solve for compatible velocities at nodes. To handle the full complexity of cloth dynamics scenarios, we have extended this base algorithm in two ways: first, towards the accurate treatment of frictional contact at any location of the cloth, through an adaptive node refinement strategy; second, towards the handling of multiple constraints at each node, through the duplication of constrained nodes and the adding of pin constraints between duplicata. Our method proves to be both fast and robust, allowing us to simulate full-size garments with more realistic body-cloth interactions compared to former methods, while maintaining similar computational timings. Our work will be submitted for publication to Siggraph 2018.

7.13. Model Predictive Control for biped walking motion generation

Participants: Pierre-Brice Wieber, Nestor Alonso Bohorquez Dorante, Nahuel Villa, Matteo Ciocca, Stanislas Brossette, Alexander Sherikov.

We proposed last year a feasible Newton scheme for nonlinear MPC by combining ideas from robust control and trust regions. This year, we applied this approach to nonlinearities that appear when adapting step durations [32]. We also investigated more thoroughly the strong recursive feasibility of our scheme [34] and how it could be adapted to situations with bounded uncertainty [29]. Finally, we proposed a new approach to collision avoidance based on separating planes [38].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- CIFRE PhD Thesis with Schneider Electric (Rami Sayoud), starting 01 January 2018.
- SAFRAN contract (August-December 2017) on the simulation of a weaving machine (F. Bertails-Descoubes)

9. Partnerships and Cooperations

9.1. Regional Initiatives

- Christophe Prieur and Bernard Brogliato are coordinator and member (respectively) of the Labex Persyval project e-Baccuss (2016-2018).
- Pierre-Brice Wieber is co-coordinator of the Labex Persyval project RHUM (2015-2018).

9.2. National Initiatives

- Vincent Acary and Bernard Brogliato are members of the Inria IPL Modeliscale (coordinator: Benoit Caillaud, Inria Rennes).
- Vincent Acary and Bernard Brogliato are members of the FUI project Modeliscale (coordinator: Benoit Caillaud, Inria Rennes).

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. 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-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.

9.3.1.2. 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.

9.4. International Initiatives

9.4.1. Inria International Labs

- Inria-Chile: two engineers supervised by Vincent Acary (Stephen Sinclair and Salomé Candela)

9.5. International Research Visitors

9.5.1. Visits of International Scientists

- Jozsef Kovecses (McGill University, Mechanical Engineering).
- Alexandre Derouet-Jourdan (OLM Digital, Japan).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Conference Program Committees

- Pierre-Brice Wieber, Associate Editor for Humanoids 2017 and ICRA 2018.
- Florence Bertails-Descoubes, Program Committe member for ACM Siggraph 2018, Eurographics 2018, and ACM-EG Symposium on Computer Animation 2017.
- Vincent Acary, Program Committe member for 9th European Nonlinear Dynamics Conference (ENOC 2017) in Budapest, Hungary.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

- Bernard Brogliato is Associate Editor for ASME Journal of Nonlinear and Computational Dynamics.

- Bernard Brogliato is Associate Editor for Nonlinear Analysis: Hybrid Systems.
- Pierre-Brice Wiever is Associate Editor for IEEE Transactions on Robotics.

10.1.2.2. Reviewer - Reviewing Activities

- Arnaud Tonnelier is reviewer for Physical Review E and Journal of Computational and Nonlinear Dynamics
- Vincent Acary, reviewer for Computer Methods in Applied Mechanics and Engineering (CMAME), Engineering Structures, IEEE Transactions on Haptics, International Journal for Numerical Methods in Engineering, Journal Sound and Vibrations, International Journal of Geological Engineering, Comptes Rendus de l'Académie des sciences, ASME Journal of Computational and Nonlinear Dynamics, Multibody systems Dynamics
- Bernard Brogliato, reviewer for IEEE Transactions on Automatic Control, Optimization Letters, Multibody System Dynamics, SIAM journal on Optimization and Control, Automatica, Journal of Optimization Theory and Applications, SIAM Journal of Applied Dynamical Systems, etc.

10.1.3. Invited Talks

- Bernard Brogliato was invited speaker at the Sliding Mode Control summer school in Graz (September 2017).
- Florence Bertails-Descoubes was invited talk at the Institut Jean le Rond d'Alember seminar in Paris (September 2017).

10.1.4. Research Administration

- Bernard Brogliato was member of the Commission d'Orientation Scientifique (COS) of Inria Grenoble until June 2017.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master : Florence Bertails-Descoubes, module IRL (Introduction à la Recherche), 1.5 éq TD, ENSIMAG 2A.

Master : Vincent Acary, 17H éq TD Systèmes dynamiques, ENSIMAG 2A.

10.2.2. Supervision

HdR : Florence Bertails-Descoubes, Numerical Modeling of elastic slender structures subject to contact and friction: From dynamic simulation to inverse static design, Grenoble Universités. Defended the 30th of May, 2017.

PhD : Alejandro Blumentals, Numerical modelling of thin elastic solids in contact. Defended the 3rd of July, 2017. Supervised by B. Brogliato and F. Bertails-Descoubes.

Alexandre Vieira, Optimal Control of Linear Complementarity Systems, October 2015, B. Brogliato and C. Prieur.

Nestor Bohorquez, October 2015, P.-B. Wieber.

Nahuel Villa, October 2016, P.-B. Wieber.

Matteo Ciocca, March 2017, P.-B. Wieber and T. Fraichard (Inria team Pervasive Interaction).

10.2.3. Juries

- Bernard Brogliato was member of the HdR jury of Laurentiu Hetel (CR CNRS, LAGIS Ecole Centrale de Lille), 14 juin 2017.
- Guillaume James was a referee for the PhD thesis of Huong Le Thi, Université de Nice (16 June, 2017).

- Bernard Brogliato was member of the HdR jury of Alexandre Kruszewski (MdC Ecole Centrale de Lille), 12 décembre 2017.
- Bernard Brogliato was member of the PhD thesis jury of Maxime Feigensicht (11 décembre 2017), Inria Lille.
- Bernard Brogliato was member of the PhD thesis jury of Sébastien Crozet (08 décembre 2017) , CEA LIST.
- Florence Bertails-Descoubes was member (examiner) of the PhD thesis jury of Vincent Barrielle (24 novembre 2017), CentraleSupélec, Rennes.
- Vincent Acary, member of Ph.D. Thesis committee of Clara Issanchou (25 September 2017), Universite Pierre et Marie Curie .

10.3. Popularization

Alejandro Blumentals and Florence Bertails-Descoubes have participated in the new showroom "login", by setting up a fiber demo. The demo allows a user to manipulate a real fiber by moving and twisting the ends, creating self-coiling structures called plectonema. In parallel to real manipulations, a simulation reproduces in real-time the deformations of a rod undergoing the same constraints, which reveals similar patterns compared to the real experiment. The simulation relies upon the optimal control framework set up by Alejandro Blumentals in his PhD thesis, which allows to simulate the quasistatic deformation of a thin elastic rod in the presence of self-contact.

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