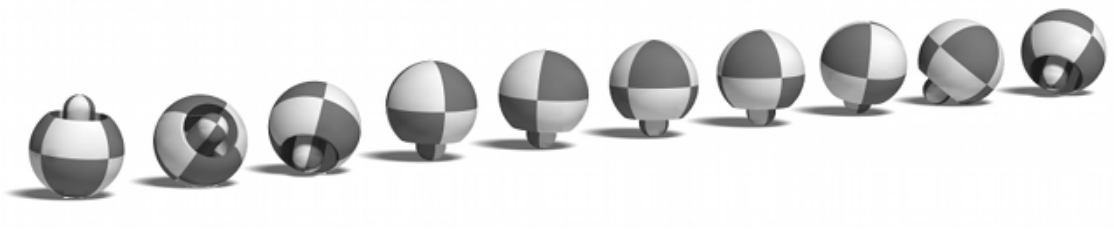
Sixth Symposium of the
European Network for Nonsmooth Dynamics (ENNSD)
September 6-7, 2017, Eindhoven University of Technology, The Netherlands



The program will be structured in 4 themes:

- Time simulation/numerical methods for non-smooth systems
- Modelling of non-smooth mechanical systems
- Dynamic analysis of non-smooth systems
- Control of non-smooth systems

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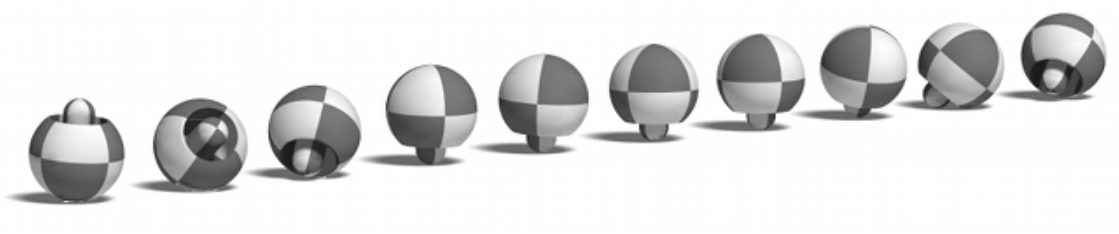


Program September 6th

Session 1: Time simulation/numerical methods for non-smooth systems

08:30-08:50: Welcome, coffee
08:50-09:00: Opening

09:00 – 10:00
Improved splitting methods for 3D frictional contact problems
Olivier Brüls, University of Liège, Belgium

10:00 – 11:00
Improvements of the Moreau--Jean time integration scheme for multi-body systems with clearances and large rotations
Vincent Acary, INRIA, France

11.00-11.30: Break

11.30-12.30
Time-stepping scheme for mechanical systems with unilateral constraints and time-delays
Wim Michiels, KU Leuven, Belgium

12.30-14.00: Lunch

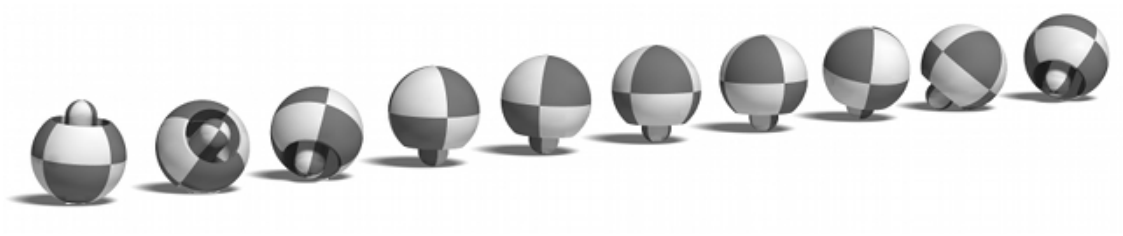
Session 2: Modelling of non-smooth mechanical systems

14.00- 15.00
A non-smooth model of borehole propagation for directional drilling
Emmanuel Detournay, University of Minnesota, U.S.A.

15:00-15:30: Break

15:30-16:30
Dynamics simulation of mechanical systems: models, algorithms, and challenges
Jozsef Kovecses, Mc Gill University, Canada

18:30-…: Dinner



Program September 7th

08:30-09:00: Welcome, coffee

Session 3: Dynamic analysis of non-smooth systems

09:00-10:00
Self-resonance owing to dynamical contact interactions
Malte Krack, University of Stuttgart, Germany

10:00-11:00
Modeling, analysis and experiments of systems with anisotropic dry friction
Remco Leine, University of Stuttgart, Germany

11:00-11:30: Break

Session 4: Control of non-smooth systems

11.30-12.30
Reference spreading hybrid control - Theoretical, numerical, and experimental aspects
Alessandro Saccon, Eindhoven University of Technology, The Netherlands

12.30-14.00: Lunch

14:00-15.00
Time-varying evolution variational inequalities: Well-posedness and output regulation
Aneel Tanwani, LAAS-CNRS, France

15.00-15.30: Break

15.30-16.30
Set-point control of motion systems with uncertain set-valued friction
Ruud Beerens, Nathan van de Wouw, Eindhoven University of Technology, The Netherlands, Delft University of Technology, The Netherlands, University of Minnesota, U.S.A.

The abstracts of the talks are included below.

1. Time simulation/numerical methods for non-smooth systems

Olivier Brüls
University of Liège, Belgium

Title: Improved splitting methods for 3D frictional contact problems

Abstract: Splitting methods [1] have been developed in order to decompose the equations of motion of a nonsmooth mechanical system into a smooth subsystem and nonsmooth contributions. Then, a higher-order time-discretization method can be used for the smooth subsystem whereas the nonsmooth terms are solved using a first-order time-discretization. Compared to the Moreau-Jean scheme, this approach improves the quality of the numerical solution especially for the representation of the vibrating response of flexible bodies. Also, all the constraints can be exactly verified both at the velocity and position levels. However, the couplings between the equations of the different subsystems resulting from the splitting may penalize the numerical efficiency of the complete procedure.

This talk discusses a new splitting strategy which intends to minimize the coupling terms between the different subsystems. In this way, the different subsystems can be solved at each time step in a purely sequential manner. This strategy significantly accelerates the convergence of the nonlinear problem to be solved at each time step and it also simplifies the practical implementation in a simulation code. The proposed method is implemented in OOFELIE, a general-purpose finite element package, which allows the analysis of finite element models involving 3D frictional contact conditions.

[1] O. Brüls, V. Acary, and A. Cardona. Simultaneous enforcement of constraints at position and velocity levels in the nonsmooth generalized-alpha scheme. *Computer Methods in Applied Mechanics and Engineering*, 281:131-161, 2014.

Vincent Acary
INRIA, France

Title: Improvements of the Moreau--Jean time integration scheme for multi-body systems with clearances and large rotations

Abstract: The Moreau--Jean time integration scheme is known to be a very robust scheme for solving multi-body systems with contact, impact and friction. Nevertheless, it suffers from some drawbacks: its intrinsic low--order, the violation of constraints at position level and a rough treatment of finite rotations. In this talk, we want to discuss recent improvements that allows to circumvent these weaknesses. Especially, we will demonstrate the efficiency of new schemes for solving complex mechanisms that come from industrial applications. Indeed, they allow to perform designs of experiments using Monte-Carlo simulations for computing the influence of clearances in electrical circuit breakers of Schneider Electric. This design of experiments result in robust estimation of reliable manufacturing tolerances with the respect to the functional conditions of the linkages.

Wim Michiels
KU Leuven, Belgium

Title: Time-stepping scheme for mechanical systems with unilateral constraints and time-delays

Abstract: Many mechanical systems operate in environments with unilateral position constraints that induce impulsive dynamics, while time-delays appear in the force terms. The motion of these systems is expressed in terms of delay measure differential inclusions. The velocity of solutions then becomes a function of special bounded variation in time, and solutions will continue after accumulating impacts. We prove local existence of solutions in the single-constraint case and provide a simulation algorithm to compute the solutions. Sufficient conditions are presented on the system dynamics that guarantee that the algorithm converges. Numerical results illustrate the performance of the algorithm.

2. Modelling of non-smooth mechanical systems

Emmanuel Detournay
University of Minnesota, U.S.A.

Title: A non-smooth model of borehole propagation for directional drilling

Abstract: Drilling geometrically complex boreholes in the subsurface has been made possible with the development of downhole tools that steer the bit. The talk presents a nonlinear model of borehole propagation that can be used to predict the bit trajectory, design the bottom-hole assembly (BHA), or be used in a model-based controller of rotary steerable systems to track a planned well path and mitigate directional instabilities that lead to spiraled boreholes.

As a preamble, key features of a linearized model of borehole propagation are first summarized. We show that the the evolution of the borehole inclination is governed by a delay differential equation (DDE), with the spatial delays corresponding to the positions of the stabilizers behind the bit. The DDE is formulated from considerations involving (a) a bit/rock interaction law that relates the force and moment on the bit to its penetration into the rock; (b) kinematic relationships that describe the local borehole geometry from the bit motion; and (c) a beam model of the bottom-hole assembly (BHA) that expresses the force and moment at the bit as functions of the loads applied on the BHA, The delay nature of the governing equation reflects the geometrical constraints imposed by the stabilizers, which, by forcing the BHA to espouse the existing borehole, affect the force and moment at the bit and ultimately the drilling direction.

Next the incorporation of essential nonlinearities in the model of borehole propagation, namely over-gauging of the borehole and saturation of the bit tilt, is discussed. Over-gauging of the borehole causes the stabilizers to contact the borehole either on the “low” or on the “high” side of the borehole (assumed to be planar) or not to contact at all, while saturation of the tilt effectively decouples the side force on the bit from the bit inclination relative to the borehole. These nonlinearities are shown to significantly affect the trajectory of the bit and its directional stability. We discuss how to treat the non-ideal stabilizers as linear complementary problems within the framework of the borehole propagation model. The talk concludes with a presentation of results of numerical simulations — both the transient and the quasi-stationary response — with an emphasis on the dependence of the solution on the borehole over-gauging. Situations where the directional drilling system is either stable or unstable are investigated, in particular the convergence of the solution towards a limit cycle, reflected by regular oscillations of the borehole trajectory, when the system is directionally unstable.

Jozsef Kovecses
Mc Gill University, Canada

Title: Dynamics simulation of mechanical systems: models, algorithms, and challenges

Abstract: Mechanical system models are generally composed of basic building blocks such as rigid body and deformable body models that represent the material components of the physical system. A key aspect is the consideration of the interactions among these basic elements. Such interactions can occur at different time scales giving rise to the concepts of finite and impulsive motions. Physical interactions can have a bilateral or unilateral nature and can generally be modelled by either constraints or constitutive relations. This then gives rise to the mathematical models with different possible structures. In this presentation, we will discuss the possible models motivated by physical considerations, the related algorithms, and highlight challenges particularly associated with friction representations and system models with bilateral and unilateral constraints.

3. Dynamic analysis of non-smooth systems:

Malte Krack
University of Stuttgart, Germany

Title: Self-resonance owing to dynamical contact interactions

Abstract: This talk addresses a mechanical system consisting of a beam under harmonic excitation and an attached sliding body. Experimental observations demonstrated the system's capability to passively re-arrange the slider along the beam to achieve and maintain resonance in a wide frequency band around the beam's first bending mode. This behavior could be useful for broadband energy harvesting or vibration absorption. In this talk, an attempt is made to explain this intriguing behavior. It is concluded that the self-adaptive behavior relies on a small clearance between slider and beam, which gives rise to dynamical contact interactions. Both friction and backlash are found to be responsible for moving the slider along the beam to a non-trivial quasi-equilibrium position. Contact is modeled in terms of the Coulomb and Signorini laws, together with the Newton impact law. The set-valued character of the contact laws is accounted for in a measure differential inclusion formulation, and Moreau's time-stepping scheme is applied for numerical integration.

Remco Leine
University of Stuttgart, Germany

Title: Modeling, analysis and experiments of systems with anisotropic dry friction

Abstract: In the research field Nonsmooth Dynamics, isotropic spatial Coulomb friction is described as a set-valued force law using a normal cone inclusion. Herein, the set of admissible friction forces, called the force reservoir, is a disk. This friction model can be generalized to anisotropic dry friction by letting the force reservoir be a general convex set, e.g. an elliptical or rectangular shape. Such an anisotropic dry friction model, being directly expressed as a normal cone inclusion, has two important restrictions. Firstly, the sliding velocity is necessarily normal to the boundary of the force reservoir (i.e. an associated flow rule), and secondly, the force reservoir must be convex. In this talk, a more general anisotropic dry friction force law is proposed which allows for a non-associated flow rule and for a non-convex force reservoir. The force reservoir is restricted to star-shaped sets.
In the second part of the talk, an experimental setup is discussed which validates the non-associated anisotropic friction law. The experimental setup makes use of a spinning anisotropic surface and a stationary pin (pin-on-disc). Unlike in many pin-on-disc-tribometers, the friction force is measured in two orthogonal directions and the rotation angle of the disk is recorded. This setup allows to observe the friction forces for all possible sliding directions during one full rotation of the disk.
In the last part of the talk, we will focus on an instability phenomenon of a system with spatial Coulomb friction. The instability phenomenon can only take place in this system if the friction law has a non-associative flow rule. Using Lyapunov stability techniques, we will study the stability properties of this system.

4. Control of non-smooth systems

Alessandro Saccon
Eindhoven University of Technology, The Netherlands

Title: Reference spreading hybrid control - Theoretical, numerical, and experimental aspects

Abstract: Trajectory tracking for hybrid dynamical systems with state-triggered jumps is complicated due to the inevitable time mismatch between desired and closed-loop contact transitions that calls for a redefinition of the concept of tracking error. This talk will review the fundamentals of a control approach for such a class of hybrid systems that goes under the name of reference spreading hybrid control. Application of reference spreading hybrid control for closed-loop motion stabilization of mechanical and robotic systems undergoing dynamic contact transitions, by means of numerical simulations and real-world experiments [3, 4, 5], will conclude the talk.

References:
[1] A. Saccon, N. van de Wouw, H. Nijmeijer, Sensitivity analysis of hybrid systems with state jumps with application to trajectory tracking. IEEE Conference on Decision and Control (CDC), 3065--3070, 2014
[2] M. Rijnen, A. Saccon, H. Nijmeijer, On optimal trajectory tracking for mechanical systems with unilateral constraints, IEEE Conference on Decision and Control (CDC), 2561--2566, 2015
[3] G.P. Incremona, A. Saccon, A. Ferrara, H Nijmeijer, Trajectory tracking of mechanical systems with unilateral constraints: Experimental results of a recently introduced hybrid PD feedback controller. IEEE Conference on Decision and Control (CDC), 920--925, 2015
[4] M.W.L.M. Rijnen, A.T. van Rijn, H. Dallali, A. Saccon, H. Nijmeijer, Hybrid Trajectory Tracking for a Hopping Robotic Leg, IFAC PSYCO, 107--112, 2016
[5] M. Rijnen, E. de Mooij, S. Traversaro, F. Nori, N. van de Wouw, A. Saccon, H. Nijmeijer, Control of Humanoid Robot Motions with Impacts: Numerical Experiments with Reference Spreading Control, IEEE ICRA, 2017

Aneel Tanwani
LAAS-CNRS, France

Title: Time-varying evolution variational inequalities: Well-posedness and output regulation

Abstract: We study a class of evolution variational inequalities (EVIs), which comprises ordinary differential equations (ODEs) coupled with variational inequalities (VIs) associated with time-varying set-valued mappings. We first consider the problem of existence and uniqueness of solutions for this system class. Making connections to the theory of differential inclusions with time-varying maximal monotone operators, we propose well-posedness conditions on the system dynamics. Several system classes, such as, complementarity systems with external inputs can be treated within this framework. Next, we consider the problem of output regulation for such systems, where the objective is to design state feedback laws such that the output of the system converges asymptotically to the output of an exogenous system. We design both a static and dynamic feedback control for this purpose, and the derivation is based on generalizing the internal model principle. As applications, we demonstrate how control input resulting from the solution of a variational inequality results in regulating the output of the system while maintaining polyhedral state constraints. Another application is seen in designing control inputs for regulation in power converters.

Ruud Beerens, Nathan van de Wouw
Eindhoven University of Technology, The Netherlands, **Delft University of Technology, The Netherlands**, **University of Minnesota, U.S.A.**

Title: Set-point control of motion systems with uncertain set-valued friction

Abstract: It is well known that friction is a performance limiting factor in high-precision positioning systems. Indeed, the presence of set-valued friction can induce non-zero steady-state position errors, friction-induced limit cycling and large settling times. In this work, these limitations are illustrated and a control architecture for the set-point stabilization of motion systems subject to set-valued friction, including a velocity-weakening (Stribeck) effect, is presented. The proposed controller consists of a non-smooth PID term and a term that robustly compensates for the Stribeck effect. It is shown that the controller asymptotically stabilizes the set-point, and a particular design of the integrator part of the PID controller term allows for faster convergence when overshoot occurs, compared to a conventional integrator. Moreover, this controller is shown to be robust for unknown static friction, and an uncertain contribution of the Stribeck effect. Stability is shown using a Lyapunov-based stability analysis and a LaSalle-like invariance argument.