CMIS 2024

Contact Mechanics International Symposium

May 22-24, 2024
Lyon - France

cmis2024.sciencesconf.org

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HISTORY

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CMIS OBJECTIVES

The 11th Contact Mechanics International Symposium (CMIS) aims at gathering researchers interested in a broad range of topics in theoretical, mathematical, computational and experimental aspects of contact mechanics.

The symposium addresses a wide panorama of topics in the area of contact mechanics in order to reinforce interactions and collaborations between the various communities:

- Models, friction laws; wear; tribological modeling; cohesive zone models; rolling;
- Emerging computational approaches: methods, algorithms and numerical analysis;
- Mathematical analysis;
- Dynamic contact problems, instabilities;
- Nano and micromechanics of contact and multiscale approaches;
- Multiphysics and thermomechanical coupling;
- Granular materials and rigid bodies;
- Contact modeling in mechanical and civil engineering, biomechanics and geomechanics;
- Architected/textured contact interfaces
- Experiments in contact mechanics

The locations of CMIS have always been selected with the idea of providing a quiet and private environment to encourage scientific discussions among the participants.

Following such tradition, CMIS 2024 will be held at Domaine Lyon Saint-Joseph close to Lyon in France, a wonderful place, heaven of peace dedicated to study and calm.

Conference organizers

- David DUREISSEIX - INSA Lyon - LaMCoS, Lyon, France
- Anthony GRAVOUIL - INSA Lyon - LaMCoS, Lyon, France
- Michel RAOUS - LMA, CNRS-AMU-ECM, Marseille, France
- Yves RENARD - INSA Lyon - LaMCoS & ICJ, Lyon, France

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PRACTICAL INFORMATIONS

CONTACT

If you need assistance, please speak to **Sophie De Oliveira** or **Emmanuel Montero** (CMIS Secretariat) who will be happy to assist you.

VENUE / DIRECTIONS

Domaine Lyon Saint-Joseph

Domaine Lyon Saint-Joseph
38 Allée Jean-Paul II
69110 Sainte-Foy-lès-Lyon

INTERNET ACCESS / PHONE

Free WiFi access is available in Saint-Joseph.
Please put your phone in silent mode so as not to disturb the presentations

SMOKING POLICY

Saint-Joseph is a designated no-smoking building. If you wish to smoke, please do so outside the buildings.

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PROGRAM

Amphitheater is equipped with a podium, screen, microphone, laptop computer and data projector. Presenters may bring their own laptop computer.

The schedule for the sessions is important and so please respect your allotted presentation time:

- **Keynotes speakers: 30-35 minutes presentation plus 5-10 minutes for discussion/questions**
- **Session speakers: 15 minutes presentation plus 5 minutes for discussion/questions**

SOCIAL PROGRAM

LES BATEAUX LYONNAIS

PROMENADE · RESTAURANT · PRIVATIF

Thursday 23rd May

Dinner cruise on board the restaurant boat Navilys II

18:15 Departure of the Domaine St Joseph shuttle for the cruise

19:00 Boarding at 13 bis quai Rambaud, Lyon 2ème
Tram T1 or T2 - Stop « Place des archives »
Bus 63 - Stop « Claudius Collonge »

20:00 Departure of the boat for a 2:30 tour

22:30 Return to the quay

23:00 Arrival

PROGRAM

Tuesday 21

16:00 – 19:30	Registration
19:00 – 21:30	Welcome dinner

Wednesday 22

8:00 – 8:45	Registration
8:45 – 9:00	Welcoming speech
9:00 – 9:10	Dedicated to the memory of Professor Del Piero
9:10 – 9:50	Keynote 1
9:50 – 10:30	Session 1
10:30 – 10:50	Coffee break
10:50 – 12:30	Session 2
12:30 – 14:30	Lunch
14:30 – 15:10	Keynote 2
15h10 – 16:30	Session 3
16:30 – 16:50	Coffee break
16:50 – 17:50	Session 4
18:30 – 21:30	Poster party

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10:30 – 10:50	Coffee break
10:50 – 12:30	Session 6
12:30 – 14:30	Lunch
14:30 – 15:10	Keynote 4
15h10 – 16:10	Session 7
16:10 – 16:30	Coffee break
16:30 – 17:10	Session 8
18:15	Schuttle for dinner cruise
19:00 – 23:00	Social program – Dinner cruise

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- **Patrick Zulian**
  - Immersed domain approach for fluid-structure-contact interaction problems
- **Diego Hurtado Cathalifaud**
  - Minimization algorithms as solvers of rate-independent contact simulations
- **Uzair Iqbal**
  - Adhesive contact study of elastic bodies in contact using body force formulation
- **Ben Kabondo Kashala**
  - Towards robust calculations axial blade/disk attachments
- **Vineethkumar Kasula**
  - The Impact of Conductive Sphere with Flat Surface in Presence of Electric Field: A Study of Arcing and Contact Time
- **Emine Ozen**
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- **Ali Maghami**
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  - Effect of roughness on micropitting: A new geometric analysis
- **Nicola Menga**
  - The mechanics of thin viscoelastic tapes peeling: effect of frictional sliding and process geometry
- **Valentin Mouton**
  - Direct flexible multibody simulation of gear meshing including both the microscale tooth contact problem and the macroscale gearbox behavior
- **Sumit Kumar Das**
  - Varying-order NURBS discretization of 3D large deformation frictional contact problems

May 22, 2024

Tribute to Gianpietro Del Piero (1940-2020)

Born on June 11, 1940, he died on September 28, 2020 in Udine. Professor at various Italian universities, he joined in 1991 the University of Ferrara, where he was the founder of the Faculty of Engineering.

Gianpietro has been very close to our contact mechanics community not only through works he did in this field but also by organizing with Professor Franco Maceri from University of Tor Vergata (Roma) the series of "Unilateral Problems in Structural Mechanics" conferences which were organized between 1982 and 2010 alternating with the CMIS series. These conferences brought together the community of unilateral contact and that of unilateral behavior of materials such as concrete. They focused in particular on non-smooth mechanics, classical and variational formulations, mathematical and numerical aspects.

Details of his career and his main remarkable scientific contributions can be found in the already published tributes (Meccanica [1]) or given by AIMETA [2] where the fundamental nature of his research is well underlined with the presentation of his last research: "In recent years, he expanded his interest to a new topic: the research of a common basis to the phenomena of fracture, plasticity, damage and creation of microstructure, which are treated in a unified manner using incremental energy minimization as a basic analytical tool. In view of the theoretical advances he obtained in this field, he revisited the foundations of the mechanics of generalized continuums, proposing an axiomatic theory independent of the concepts of motion and inertia and able to provide a simple and unitary formulation for many classes of generalized continua."

Gianpietro was a remarkable scientist for his broad and deep vision of continuum mechanics. He put concepts into perspective in his fundamental scientific contributions. He was a very rigorous person who could work for several years on an article or the chapter of a book before publishing because he had a great concern for the precision of details.

This rigor was reflected in the exceptional quality of his uncompromising teachings. He regularly received feedback from his students several years later.

Gianpietro was among the great contemporary mechanicists who have made significant advances in continuum mechanics and in particular on the thermomechanical basis in several areas. And he was also of great modesty and simplicity.

With his extraordinary scientific, historical and humanist culture, the conversations with him were always fascinating. He loved hiking, and I took this photo during one of the last hikes we did together when he came to Marseille for some work sessions. It has been a privilege to be his friend.

Michel Raous
Marseille, February 2024

[1] Podio-Guidugli, Paolo, Remembering Gianpietro Del Piero, Meccanica, 56 (1-2), 2021, 2415-2428.
[2] AIMETA https://www.aimeta.it/index.php/notizie/162-scomparsa-di-gianpietro-del-piero

Keynote 1

Adhesive interfaces: unified model and mathematical analysis

"Dedicated to the memory of Professor Gianpietro Del Piero"

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A brief survey of the most widely used Cohesive Zone Models and models coupling unilateral contact, friction and adhesion will be first presented.

Then, a general framework for these laws will be given under the form of a unified formulation proposed by Del Piero and Raous (see [1]). This unified formulation is similar to the Generalized Standard Materials theory due to Bernard Halphen and Nguyen Quoc-Son.
It is based on :
– general laws, typically, balance of energy and dissipation principles, that is mechanical versions of the first two laws of thermodynamics,
– a set of state variables, that is an array of independent variables which fully determine the response to all possible deformation processes,
– a set of elastic potential and dissipation potentials, which are functions of state in terms of which the general laws take specific forms,
– a set of constitutive assumptions.

The various models introduced first can be deduced from this unified model by making appropriate choices of the strain energy, of the dissipation potentials, and of the constitutive functions for the normal and tangential contact forces.
This is illustrated on the RCCM model briefly recalled (see [2][3]).

The second part of this presentation is concerned with mathematical analysis of some classes of adhesion problems, including those previously considered. As these problems are formulated in the framework of continuum contact mechanics, their mathematical study is based on appropriate applications of functional analysis, nonlinear analysis, and convex analysis, in particular of variational inequalities theory, see, e.g., [4].
Some recent mathematical results, on existence and uniqueness of solutions, due to several authors, will be briefly presented.
Finally, some variational methods that ensure the mathematical consistency of the unified model previously proposed will be described in the quasi-static and dynamic cases.

References

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https://hal.science/hal-03085400v2

Session 1

On the efficient modeling of Lennard-Jones interactions between slender bodies

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The Lennard-Jones interaction potential (LJIP) models van der Waals attraction and steric repulsion between particles. It gives rise to some of the most ubiquitous intermolecular forces in nature that are often decisive for the interactions between slender bodies at micro- and nano-level. Modeling of LJIP for 3D bodies is a computationally intensive task due to the large number of particles. By coarse-graining, a discrete model can be transformed to a continuous one [1]. Furthermore, the mechanical behavior of slender bodies is well-described with beam theories [2] which allows us to pre-integrate the LJIP over the beam cross-section and simplify the underlying integral [3]. Such approach enables a study of peeling and pull-off between two elastic fibers based on the LJIP [3]. The normal component of the interaction force is shown in Fig. 1.

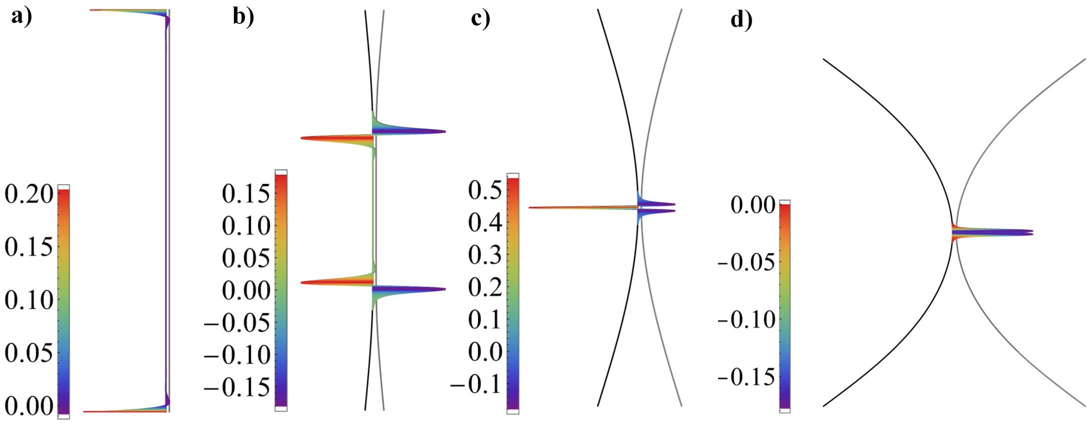

Figure 1: The interaction force plotted on the left beam. a) initial configuration; b) peeling develops; c) transition from peeling to pull; d) just before the pull-off.

Acknowledgments

This research was funded in part by the Austrian Science Fund (FWF) P 36019-N. For the purpose of open access, the authors have applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

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Siconos/numerics and FCLIB: a collection of solvers and benchmarks for solving frictional contact problems

Vincent Acary

Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, Institute of Engineering, LJK, 38000 Grenoble, France

The solution of one-sided contact problems with Coulomb friction, and its linear discrete version after spatial and temporal discretisation and linearisation, is still a subject of important research. The inherent difficulty of the problem lies in the non-montone nature of its variational inequality formulation over second order cones, which can be generically formulated as:

$$\begin{cases} Mv + f = H^\top r, \\ Hv + w + se = \tilde{u}, \\ s = \mu \|\tilde{u}_\mathrm{T}\|, \\ \mathcal{K}^* \ni \tilde{u} \perp r \in \mathcal{K}, \end{cases} \tag{1}$$

where v is the generalized velocity or displacements, M is a (semi-)definite positive matrix (mass matrix, stiffness matrix or iteration matrix), H is the global-to-local operator, f and w are vectors that depend on data. For one contact, μ is the friction coefficient, $\tilde{u}$ the modified relative contact tangent velocity or incremental displacement and $\tilde{u}_\mathrm{T}$ its tangent part, $e = (1, 0, 0)^\top$ is the normal vector and $\mathcal{K} := \{(r_\mathrm{N}, r_\mathrm{T}^\top) : \|r_\mathrm{T}\| \leq \mu r_\mathrm{N}\}$ represents the friction cone of reaction force r and $\mathcal{K}^*$ is its dual cone (details in [1–3]).

Siconos/numerics is an open-source implementation in C of a large number of numerical solvers for solving (1), including:

– first-order methods: projected fixed points and extra-gradients, Projected Gauss-Seidel (PGS) and Successive Over Relaxation (PSOR) methods, Alternative Direction Methods of Multipliers (ADMM), Acceleration methods,
– second order methods: semi-smooth Newton methods and interior points methods,
– optimization based approaches with successive convex relaxation, and proximal point algorithms,
– direct pivoting solvers for polyhedral cases (Lemke, Bard, Murty).

The implementation is modular and easy-to-use. It can used as a C API, or through its Python interface. The linear algebra is based on Blas/Lapack and HPC linear solvers (Mumps, MKL and SuperLU). It also comes with more than a hundred unit tests.

To complement this collection of solvers, more than 4000 benchmarks have been collected since 2012 in an open library called FCLIB on github. These benchmarks store data of (1) in HDF5 format, along with an API for reading and writing problems. Contributions are welcome to increase the diversity of problems from your in-house solvers.

References

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Session 2

Nonlinear contact interface problems with nonmonotone transmission conditions on unbounded domains – numerical treatment by FE and BE coupling with regularization

Joachim Gwinner

Universität der Bundeswehr München, Germany

For the first time, a nonlinear interface problem on an unbounded domain with nonmonotone transmission conditions is analyzed. The investigated problem involves a nonlinear monotone partial differential equation in the interior domain and the Laplacian in the exterior domain.

Such a scalar interface problem describes a antiplane frictional contact problem and models nonmonotone frictional contact of elastic infinite media in two or three dimensions. The variational formulation of the interface problem leads to a hemivariational inequality, which lives on the unbounded domain, and so cannot be treated numerically in a direct way.

By boundary integral methods the problem is transformed and a novel hemivariational inequality (HVI) is obtained that lives on the interior domain and on the coupling boundary, only. Thus for discretization the coupling of finite elements and boundary elements is the method of choice. In addition smoothing techniques of nondifferentiable optimization are adapted and the nonsmooth part in the HVI is regularized. Thus we reduce the original variational problem to a finite dimensional problem that can be solved by standard optimization tools. We establish not only convergence results for the total approximation procedure, but also an asymptotic error estimate for the regularized HVI.

References

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Dimensional reduction in a model of adhesive contact

Giovanna Bonfanti, Elisa Davoli and Riccarda Rossi

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We address a dimension reduction analysis for a model of adhesive contact between two thin plates, in the frame of visco-elasto-dynamics [1].

The evolution of the system is encoded by a momentum balance equation, with viscosity and inertia, for the displacement field coupled with a "boundary" equation on the contact surface describing the evolution of the adhesion in terms of a surface-damage parameter.

Due to the poor time regularity of the adhesion parameter, the resulting PDE system needs to be weakly formulated in a suitable way, reflecting its mixed rate dependent/ independent character. More precisely, we resort to an energetic-type solvability notion (introduced in [2-3]) in which the momentum balance equation holds in a variational sense, whereas the flow rule for the adhesion parameter is replaced by a semi-stability condition joint with an energy-dissipation inequality.

Our dimension reduction analysis provides the existence of solutions for two different Kirchhoff-Love type models. The first one is obtained by considering a vanishing viscosity tensor (leading, in the limit, an undamped model), and the other one is achieved in the complementary setting in which the damping is assumed to go to infinity as the thickness of the plates tends to zero.

In both regimes, the presence of adhesive contact yields a nontrivial coupling of the in-plane and out-of-plane contributions in the reduced models. In the undamped case we obtain in the limit an energy-dissipation inequality and a semi-stability condition. In the damped case, instead, we achieve convergence to an enhanced notion of solution, fulfilling an energy-dissipation balance.

References

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Multi-scale analysis of rough surface contact through FEM/BEM coupling

Rishav Shaw[1], Ivo Steinbrecher[1], Jacopo Bonari[2], Matthias Mayr[1,3] and Alexander Popp[1]

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Problems involving the contact of rough surfaces is a highly researched field with applications in many different domains. Due to the intricate geometrical complexity of the interface, determining contact variables such as traction distributions, contact stiffness, and the actual contact area is still challenging. Therefore, understanding the connection between the topological features of surface roughness and the consequent nonlinear constitutive relation at the interface is of prime importance for researchers today.

In the last decades, several semi-analytical micromechanical contact theories relying on the statistical distribution of the elevation of the asperities have been proposed. In [1], a new numerical formulation that operates on multiple scales has been introduced, where the boundary element method (BEM) is used for the solution of the rough contact problem on a micro-scale level. Then, the resulting gap-pressure relation on the micro-scale is fitted to an power law and used as a contact constitutive law in the macro-scale finite element method (FEM) model. This curve fitting approach unifies both scales but has limited accuracy at low and high contact pressure regimes.

Our current work explores a consistent coupling of both the micro- and the macro-scale within a single simulation framework to overcome the shortcomings of the previous methods. At the micro-scale, a linear elastic frictionless normal contact between a rigid rough indentor and an elastic half-space is solved using BEM. This allows to handle a very fine discretization of the interface without the need to discretize the bulk volume. For the topology of the indentor, any statistically representative microscopically rough surface can be provided as input. The surface roughness can vary over the contact surface of the macro-scale finite element model. In our examples, the rough surfaces can be generated based on their fractal parameters using the random mid-point displacement (RMD) method and the sprectral synthesis method [2]. The macro-scale model is solved using FEM, where the contact interface is discretized using mortar elements. This allows for non-matching grids on the macro-scale model. At every mortar node, the normal contact traction is calculated using the BEM algorithm, and the interface stiffness is approximated by a finite difference approach. These parameters calculated at the micro-scale are then passed back to the macro-scale model.

In this presentation, our approach for multi-scale coupling will be outlined. Various qualitative and quantitative examples will be shown to demonstrate the validity and usefulness of the proposed multi-scale approach, and its advantages and limitations will be discussed.

References

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Towards the non-linear dynamics modeling of the CEA wear testing machines: a one-dimensional predictive model of vibro-impact regimes observed in a new wear testing facility

J.L. Fayard[1,2], B. Prabel[1], P. Piteau[1], X. Delaune[1]

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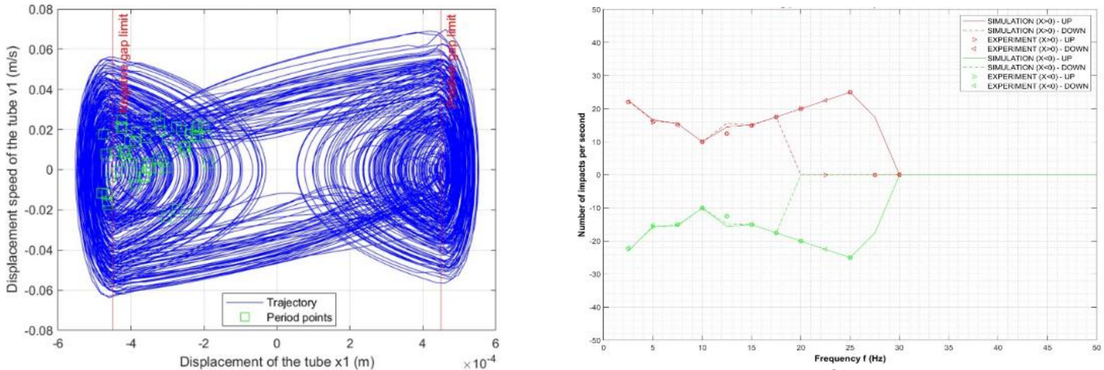
In the industrial context of pressurized water reactors (PWR) within the French nuclear power plant fleet, some of the vessel internals are subject to wear, which requires the implementation of costly maintenance strategies. Faced with these challenges, EDF and CEA aim to enhance the understanding and prediction of wear phenomena, not only to optimize maintenance operations and improve component design but also to optimize research and development efforts while ensuring the reliability of the obtained results.

Among the technical and scientific objectives set within the framework of their collaboration since 2014, the development and the improvement of wear testing equipment and its digital twin are of particular importance and considered as a priority [1].

The state of the art in the field of nonlinear dynamics modeling of mechanical systems with clearances [2] has led recent research at CEA towards the modeling of vibratory wear testing machines. Specifically, the study has concentrated on modeling the MUSE new generation tribometer and its electromagnetic actuators. Initial results from one-dimensional modeling of a single actuator have shown promise. They were validated through comparison with normal impact tests conducted on the MUSE machine (Figure 1).

In the immediate future, we plan to extend the 1D modeling to 2D, including friction during impact. Identifying the various vibratory regimes involving impact and friction, as well as the machine's bifurcations, is crucial to understand the testing apparatus dynamics. This knowledge will facilitate the development of more precise specifications for wear tests and enhance control over the necessary contact conditions for studying the phenomenon.



(a) (b)

Figure 1: One-dimensional non-linear dynamic model of the MUSE actuator: (a) chaotic trajectory obtained in the phase diagram for a sinusoidal signal at 5 Hz, (b) Comparison of the number of impacts per second obtained by simulation (solid and dotted lines) and by experiment (markers) on the X>0 (red) and X<0 (green) sides. UPward and DOWNward sweep.

References

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Approximation of frictional contact using Nitsche's methods in 3D elasto-plastic industrial problems

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Frictional, elasto-plastic multi-body contact problems play an important role in mechanical engineering. The non-linearities caused by geometric contact and frictional constraints, combined with the non-linearity in the material law result in challenging numerical problems in the forms of variational inequalities. Therefore efficient solving methods are needed. Numerical methods for contact problems have been an active field of research for many years but still new methods keep emerging. Probably the youngest member of the family is Nitsche's method, see [3]. A first application to contact mechanics was presented in [4] and a mathematical analysis for linearized kinematics has been published [2]. Unlike any other method, Nitsche's method is at the same time variationally consistent (and therefore optimally convergent) and does not introduce any additional degrees of freedom. This comes at the expense of having to evaluate the boundary traction from the continuum stresses. In this note, we describe the use of Nitsche's method to prescribe a contact (with or without Coulomb friction condition) between two elasto-plastic bodies. This corresponds to a weak integral contact condition which has some similarities with the ones using Lagrange multipliers. The goal of this talk is to present how differents industrials cases in SYSTUS/SYSWELD where we used Nitsche's methods to solve certain contact problems in the context of large deformations. The approximation strategy proposed here was implemented for the first time in the open source finite element library GetFEM [1] for contacts in small and large elastic or hyperelastic deformations with or without friction.

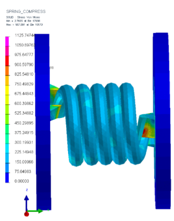

Figure 1: spring : elastoplastic multi-auto-contacts

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Keynote 2

Computational contact mechanics and machine learning: Dream team or nightmare?

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In the research field of computational contact mechanics, the integration of machine learning (ML) techniques presents a frontier teeming with both promise and challenges. This contribution explores this dichotomy, provocatively titled *"Computational Contact Mechanics and Machine Learning - Dream Team or Nightmare?"*, by delving into two pivotal applications from our research group.

Firstly, we examine the modeling and simulation of rough surface contact. Traditionally approached through Boundary Element Methods (BEM) in computational mechanics [1], this area has recently witnessed a paradigm shift with the introduction of data-driven surrogate modeling techniques. These ML-based methods, standing as an alternative to BEM (or FEM), have shown potential in capturing complex behaviors of rough surface interactions. Our investigation evaluates the efficacy of these techniques in replicating the nuanced physics that BEM adeptly handles, assessing their accuracy, computational efficiency, and applicability in diverse scenarios [2] .

Secondly, the contribution transitions to the realm of continuum contact modeling in 2D and 3D frameworks, where (Mortar) Finite Element Methods (FEM) have been the cornerstone for many years. Here, we explore the integration of Physics-Informed Neural Networks (PINNs), a cutting-edge ML approach [3]. PINNs bring a novel perspective with their ability to incorporate physical laws into the learning process, potentially offering enhanced predictive capabilities and reduced computational costs [4]

This exploration into both domains seeks to offer a balanced perspective on the role and potential of ML in contact mechanics. While ML techniques, like data-driven surrogate models and PINNs, present exciting opportunities for advancing computational efficiency and predictive accuracy, they also bring forth challenges in terms of model interpretability, generalizability, and the fidelity of physical law representation.

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Session 3

Collision detection and contact simulation for dynamics of flexible bodies with the floating frame of reference formultion

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Contact simulation plays an important role in modelling mechanical systems with interactions between objects. To capture the dynamic behaviour of the system models involving contact, *collision detection* methods need to be applied to determine the contact position, the direction of contact force, etc. Dynamic models with contacts are formulated accordingly to solve the contact force. Collision detection and dynamic formulation can be challenging, especially for mechanical systems consisting of flexible components, as the geometric boundaries keep changing during the simulation.

Common methods consider collision detection as a geometric problem separated from the dynamic formulation. They usually approximate the shape of objects with geometric primitives or meshes. The approximation may lead to error, such as in the example in Fig. 1(a), where a bending beam is geometrically approximated by a group of capsules. To increase the accuracy, a larger number of geometric primitives or a denser mesh is required, which can significantly increase the computational cost.

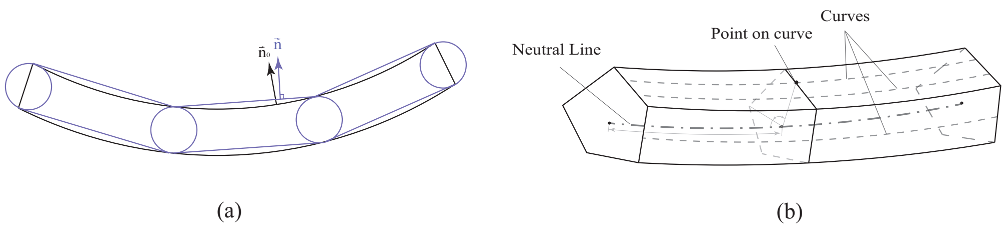

Figure 1: (a) Error of contact normal direction in a bending beam approximated by capsules, (b) curve-based representation for beam.

In this work, a *curve-based* collision detection method that is more consistent with the dynamic formulation is proposed. For structural components undergoing small deformation, the floating frame of reference (FFR) formulation is often used to represent the motion by decomposing it as the addition of the rigid body motion and the local deformation [1]. In this formulation, a shape function matrix $\mathbf{S}$ is used to describe the shape and deformation distribution. The proposed curve-based method employs a group of curves using the same shape function matrix $\mathbf{S}$ to describe the geometric boundaries more accurately, as demonstrated in Fig. 1(b). The collision detection is broken down into curve-to-curve subproblems, each of which can be solved straightforwardly. With the information provided by the collision detection method, contacts can then be formulated as unilateral constraints, and the dynamic of the flexible system can be solved. Case studies of flexible beams with contact have been implemented using the FFR formulation, showing that the contact simulation with the curved-based collision detection performs well in both accuracy and efficiency.

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Immersed domain approach for fluid-structure-contact interaction problems

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We present an embedded approach for the numerical solution of contact problems between multiple elastic structures immersed in a fluid flow.

Our parallel approach is designed to simulate the full dynamics of a bio-prosthetic heart valve. We model the blood-valve interaction, the blood-aortic wall interaction, and the contact among leaflets during the valve closure.

The solid bodies are modeled as hyperelastic and anisotropic materials, whereas the fluid is regarded as a Newtonian flow. The mathematical modeling of such material properties and the contact mechanics give rise to a large-scale nonlinear problem that is both challenging and computationally expensive to solve.

We employ a localized version of the L^2-projection for handling the fluid-structure volumetric coupling and a variant of the mortar method for coupling the surfaces of the structures in contact.

In this contribution, we describe our approach to solving the contact problem between the immersed solids. First, we provide an algorithmic overview of the FSI algorithm, which is specifically designed to include and fully resolve the contact constraints. Second, we illustrate our parallel large-scale solution strategies for solving the arising contact sub-problem in a non-smooth optimization framework.

The proposed strategy is validated and finally employed to model the dynamics of a bio-prosthetic heart valve placed in the aortic root (Figure 1)

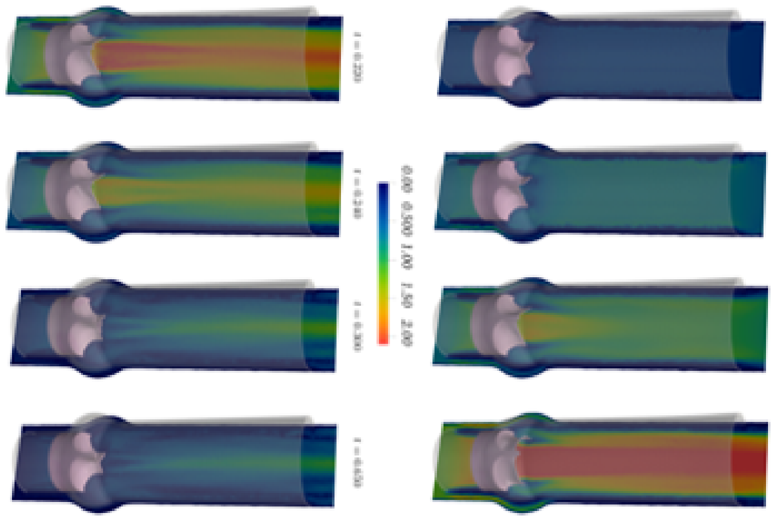

Figure 1: Numerical simulation of a bio-prosthetic heart valve placed in the aortic root.

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Recent advances and challenges in tribological third body simulation

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Mechanical contacts in dry conditions generate surface degradation and wear material production, and experimental evidences show that any sufficiently mature contact is characterized by a layer of interfacial solid matter trapped in the interface and generally called Third Body [1]. Tribological literature is prolific on this phenomenon, because it is well-known to exert a strong control on the frictional behavior of a sliding contact and on its wear rate and regime. This layer, however, if often disregarded in computational contact mechanics, probably because of its complexity, although a few attempts (for example using Discrete Element Modelling or Molecular Dynamics) revealed to be very instructive [2, 3].

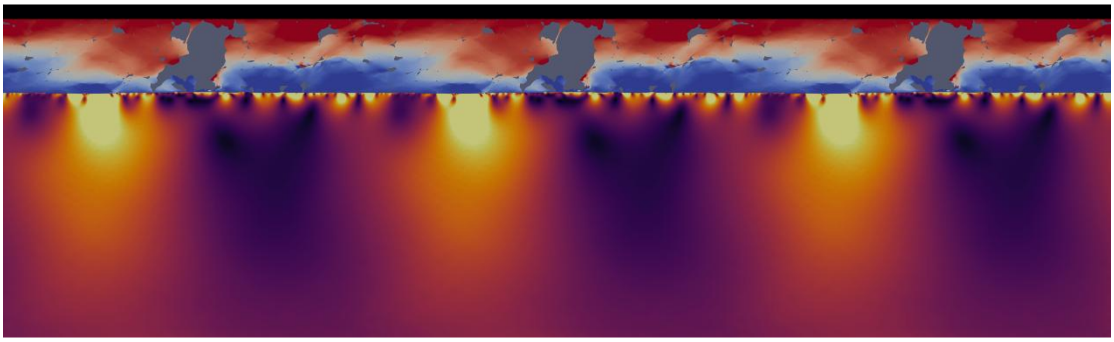

Figure 1: Illustrative simulation of the confined shearer flow of an agglomerated third body, and associated stress concentrations in the sub-surface.

In the past years, several simulation campaigns have been undertook using a novel numerical technique called the Multibody Meshfree Approach (implemented in the open code MELODY, Figure 1), which aims at coupling discrete and continuum mechanics in a common framework. This is particularly appropriate for third bodies, which can exhibit various rheological behavior ranging from the granular to the plastic or the agglomerated regimes. In this communication, we present a general overview of the main results obtained using this framework, including (i) the influence of various local properties of the third body particles on their collective accommodation regime [4], (ii) the local energy budget of the third body sheared flow and its implications on macroscopic friction, (iii) the complex mixing processes taking place in this solid flow, (iv) the stick-slip phenomena that arise when such a third body is coupled with the elastic compliance of the contacting solids, and (v) the consequences of the third body flow regime on the stress patterns and fluctuations endured by the surfaces.

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Elastic Shakedown and Roughness Evolution in Repeated Elastic-Plastic Contact

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Surface roughness emerges naturally during fracture, chemical deposition, mechanical removal of material, indentation, plastic deformation, and other processes. Here, we employ continuum-scale simulations to show how roughness which is neither self-affine nor Gaussian emerges from repeated elastic-plastic contact of rough and rigid surfaces on a flat elastic-plastic substrate. Roughness landscapes change at each contact cycle, but appear to approach a steady-state long before the substrate stops deforming plastically, a stage of contact called elastic "shake-down" [1]. We show that a simple dynamic collapses the emerging power-spectral density. This demonstrates that the multi-scale nature of the emerging roughness is encoded in the first few indentations. In contrast to macroscopic roughness parameters, such as the root-mean-square of heights, the roughness at small scales and the skewness of the height distribution of the resulting roughness do not show a steady-state, the latter vanishing asymptotically with contact cycles [2].

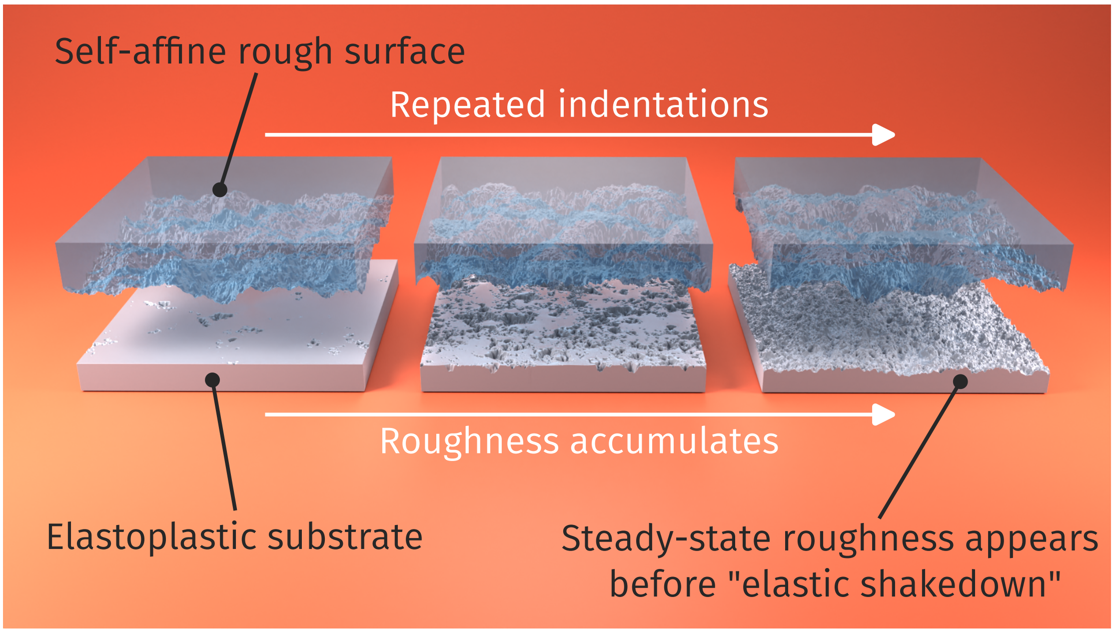

Figure 1: Repeated indentations with different rough surfaces create a new, emerging roughness profile.

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Session 4

A multiscale a priori reduced-order modelling method for problems with multiple frictional contact interfaces

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Despite continuous progress in computational contact mechanics, simulating a complex structure with multiple frictional interfaces still requires a large computational time due to multiple sources of non-linearity: contact and friction status change with deformation, frictional dissipation, and possible rotations in the transformation. This cost may induce limitations for industrial cases involving architectured materials [1], like spiral strand wire ropes used in offshore engineering which motivated this work [2].

A well-known strategy to circumvent such limitations is to project the full-order problem on a reduced-order basis (ROB) of the original problem through various reduced-order modeling (ROM) strategies. Classical ROM approaches with contact conditions remain limited to a-posteriori methods for parametric problems, mainly limited to frictionless contact [3, 4]. Their application to frictional problems with the change in contact conditions remains an open question, specifically for the cases involving the propagation of sliding/adhesion fronts.

The considered resolution strategy is based on the LATIN (Large Time Increment) solver combined with the a priori ROM based on the Proper Generalized Decomposition (PGD). The LATIN is a non-incremental solver that features a robust treatment of contact conditions with two alternating search directions and a global space-time approach that enables the use of ROM on the fly during the computations. Spiral strand wire rope mechanics are marked by local solutions at wire contact interfaces with shorter wavelength when compared to the characteristic rope length. A well-suited strategy is thus adopted, with a multiscale domain decomposition method (DDM) based on the LATIN method [5].

Simple 1D and 2D problems will be presented to illustrate the concepts of the strategy and its performance. To ensure accurate prediction of the local solution on several frictional interfaces, it is crucial to control the local error with an appropriate convergence indicator. The convergence rate of the method also strongly depends on the search directions of the LATIN solver. The method efficiency also depends on the size and quality control of the ROB that is progressively built with PGD, so as on the choice of DDM coarse scale problem. With adapted choices, it is possible to get a significant computational gain for the same accuracy.

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Friction for a rolling adhesive viscoelastic cylinder: effect of Maugis parameter

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In a series of beautiful experiments, Barquins [1] proved that due to van der Waals attractive forces and the difference in work of fracture in opening and closing crack in viscoelastic solid, a rigid cylinder could roll on an inclined rubber plane with a friction force which depends on velocity, but which was approximately equal for negative or positive normal force. Further in other sets of experiments with Charmet [2], he found that contact area increased with velocity and that rolling was possible under negative loads even 50 times higher than the static pull-off force. These experimental findings has never been compared accurately with theoretical predictions. Here, we consider the case of a standard linear material and find that the friction force is approximately the same for negative or positive loads only for sufficiently large Maugis-Tabor parameters λ [3] i.e. sufficiently soft and large cylinders as the rubbery cylinders of Barquins, and otherwise differs considerably. Likewise, we find increase of contact area and of pull-off load only for sufficiently large Maugis-Tabor parameter. We provide comprehensive numerical results for pull-off force and friction. The results obtained are in qualitative agreement with reported experimental results by Barquins. In general, for small λ, friction is very small, even smaller than the Hunter-Persson solution [4] as an effect of the deviation from Hertz solution due to the Lennard-Jones law when dealing with very small cylinders. The interesting case of large λ shows a more complex role of adhesion which gives non-monotonic dependence on both normal load and speed. In the case of a sliding body, the results provided are in qualitative agreement with the experiments of Grosch [5] on smooth glass surfaces. Nevertheless, actual comparison with experiments is made difficult by the fact that on smooth surfaces, other mechanisms may contribute to rubber friction [6-7-8], due to the role of shear stresses, and possible travelling Schallamach waves, makes comparison with experiments more complex as there are additional mechanisms for friction.

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Direct numerical simulation of sliding rough contact

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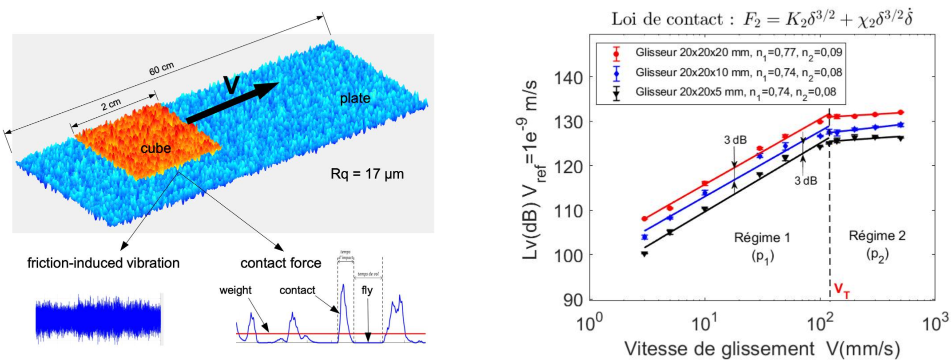
We have performed a direct numerical simulation of the vibration induced by the sliding friction in rough surfaces. The configuration is the following. A small rigid cube is set down on a horizontal large plate. The bottom face of the cube and the top face of the plate have random Gaussian surfaces of roughness 17 μm and correlation length 80 μm. The cube slides at a constant speed V in the range $3 - 500$ mm/s. The gravity maintains the contact. During the sliding, mechanical contacts between surface asperities induce a vibration of the thin elastic plate.

In Figure 1 is shown the evolution of the vibrational level L_v versus sliding speed V. We found that below $V_T = 120$ mm/s, the RMS vibrational speed v in the plate evolves as $v \propto V^\beta$ with $\beta = 0.75$. Beyond this transitional sliding speed, v follows the same power law but with the exponent $\beta = 0.1$.

The analysis of the total contact force between the cube and the plate reveals the existence of two regimes. Below V_T, the contact is always maintained (creeping regime) and the mean contact force is equal to the cube weight. But beyond V_T, the contact force may reach zero and losses of contact appear and (flying regime). The first losses of contact appear at a sliding speed well predicted by a unit value of Froude's number $Fr = V_T^2/Rg$ where $g = 9.81$ m/s^2 and $R = 30\,\mu$m is the radius of curvature of the mass centre of the cube (estimated in quasi-static condition).



(a) (b)

Figure 1: Friction-induced vibration by rough surfaces in sliding contact: (a) finite element mesh in the undeformed configuration, (b) evolution of vibrational level versus sliding speed for three thicknesses of the cube.

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May 23, 2024

Keynote 3

Memory effects in soft matter friction: the role of sliding inhomogeneities

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Unsteady-state frictional situations have long been recognized to involve memory effects. A typical example is the response of a contact when the slip rate is changed suddenly from one value to another greater value: a positive jump in the frictional stress followed by a long-term decay to steady-state is then observed. In order to describe these observations, phenomenological approaches such as the seminal state-and rate model by Rice and Ruina [1] have been introduced where phenomenological state variables account for the fading memory of the contact. However, the underlying physical mechanisms behind state-and-rate friction laws remains largely debated.
In this study, we tackle memory effects in friction from the perspective of the transient sliding inhomogeneities which result from the deformation of finite size contact areas during unsteady state sliding. For that purpose, a smooth, single-asperity, contact interface between a deformable rubber and a rigid spherical probe is perturbed by the application of either non rectilinear sliding motions (Fig. 1a) or a velocity step. In the case of non rectilinear motions, we show from measurements of the displacement fields within the contact (Fig. 1b) that stress and strain inhomogeneities keep a memory of the past trajectories. As a consequence of these memory effects, the friction force may no longer be aligned with respect to the sliding trajectory (Fig. 1c). These observations are adequately accounted for by a friction model which takes into account heterogeneous displacements within the contact area [2]. When a velocity dependence of the frictional stress is incorporated within the model, unsteady state regimes induced by velocity steps are also adequately described. The good agreement between the model and experiments outlines the role of space inhomogeneities in memory effects involved in soft matter friction.

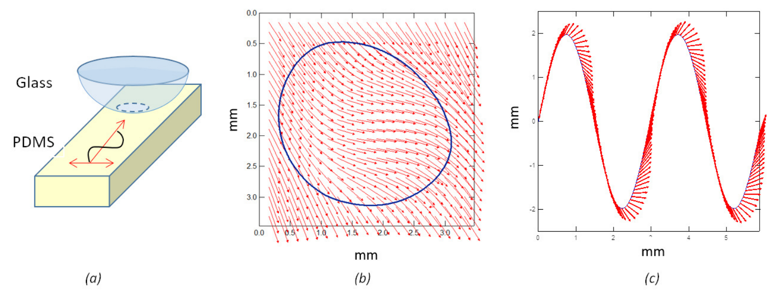

Figure 1: Curvilinear sliding of a silicone substrate along a sinus wave trajectory. (a) schematic of the experiment; (b) vector plot of the sliding velocity field. (c) vector plot of the friction force along the sinus wave trajectory (blue line) ;

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Session 5

Solving adhesive rough contact problems with atomic force microscope data

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This contribution presents an extension of the finite element discretization technique based on the eMbedded Profile for Joint Roughness (MPJR) interface finite element originally described in [1]. The method has been developed to solve high-fidelity contact mechanics simulations accounting for surface textures and microscopic roughness. An interface characterized by any arbitrary complex shape can be globally discretized as smooth, while any deviation from planarity is embedded into the interface finite elements to be used as a correction of the normal gap function computed if the surfaces were flat.

The method have been efficiently applied to 2D and 3D contact problems involving nominally flat rough surfaces, frictional contact with viscoelastic substrates, or indenters of any arbitrary shape, including wavy or spherical indenters [2, 3]. In combination with a phase field approach to brittle fracture, the MPJR approach has been employed in [4] to address complex nonlinear coupled problems of contact-induced fracture, with very good agreement when compared to available experimental trends.

The current study analyzes the possibility of taking into account additional field variables at the interface level, directly acquired through an Atomic Force Microscope (AFM) data campaign on PS-LDPE samples, composed by a polystyrene (PS) matrix and low-density polyethylene (LDPE) as doping component, Fig. 1a. Experimental height, adhesion and dissipation fields have been exploited to formulate the interface constitutive model, allowing for an accurate solution of the multi-fields contact problem, Fig. 1b.

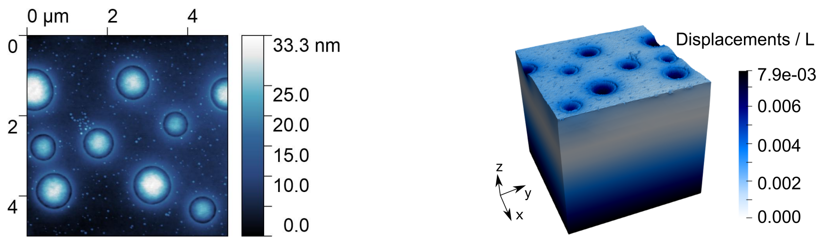

Figure 1: (a) Height field of the PS-LDPE sample, (b) Normalised displacements magnitude of a smooth solid in contact with a PS-LDPE sample.

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A damage-based wear model using the thick level set approach

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Wear is a surface degradation mechanism that results in a progressive surface material removal. It may originate from a variety of different mechanisms on a microscopic scale, and is very complex to model. The most commonly used wear models are empirical, and they sometimes fail to accurately predict wear evolution.

The study presented here attempts to define a wear modeling approach based on the framework of continuum thermodynamics. Following earlier work by Dragon-Louiset and Stolz [1], wear evolution is represented here by the propagation of the contact surface which is treated as a discontinuity boundary which separates the unaltered, to-be-worn bodies from an interfacial third body. Its propagation is associated with an energy dissipation which is expressed by an energy release rate. This energy release rate can be interpreted as the thermodynamic driving force associated with wear evolution.

A wear criterion is then proposed, in which wear evolution is assumed to be the consequence of a progressive accumulation of degradation in a near-surface material layer. To this end, a damage-like variable is introduced and the damage evolution problem is tackled using the thick level set approach [2]. In this method, the local damage evolution law is substituted by a non-local level set propagation law. As a result, wear is indirectly driven by the propagation of the level set and occurs when the surface damage value reaches a threshold.

Finally, this model is implemented within a finite element simulation process [3] and some preliminary numerical results are obtained on a two-dimensional cylinder-plane contact submitted to a cyclic loading. As expected, the results exhibit a two-stage wear evolution: first, damage progressively increases over the cycles in a near-surface material layer but the surface damage value has not reached the threshold. As a result, wear does not occur during this initial incubation time. After a certain number of cycles, the surface damage reaches the threshold which triggers the onset of wear.

This wear modeling framework should be further developed in future work. Prospects include the improvement of the numerical simulation process integrating this kind of wear model, and the more precise identification of a wear damage law. In addition, alternative methods could be explored to treat the damage evolution problem [4].

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Master-master contact formulation on explicit DEM solver

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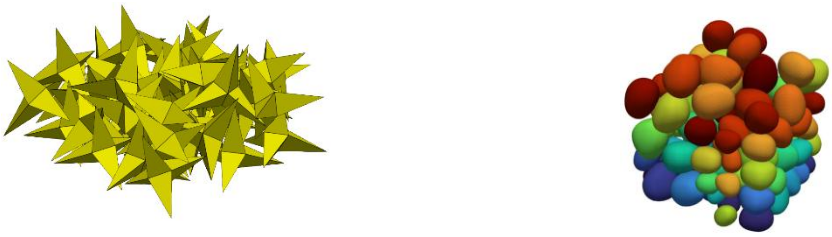
In this work, we propose an explicit solver for the Discrete Element Method (DEM), which considers the master-master contact formulation and its degenerations [1] to treat contact between particles. Previous developments such as [2] proposed such contact approach in implicit DEM with general polyhedra. In present work, these ideas are adapted to implementation in an explicit context, with both polyhedra and NURBS-based particles (see Figure 1).



(a) (b)

Figure 1: (a) Polyhedral particles and (b) NURBS-based particles.

As here particles are considered rigid bodies, one needs to integrate both displacement and rotation degrees of freedom. The bases of the time-integration of rotations are the Lie group methods presented in [3], which involve rotation pseudo-vector integration along time in a multibody dynamics context. Our choice is adopting the so-called Rodrigues parameters for rotations, due to some algebraic conveniences. We work with an updated Lagrangian scheme and integrate both translations and rotations in material frames of particles. Two algorithms for integration were tested, successfully: Euler and 4th order Runge-Kutta.

To handle contact between particles, the master-master contact formulation was completely adapted for the evaluation of contributions on the explicit integration scheme. An algebraic simplification was performed on the original equations proposed in [1], showing the contact contributions on a straightforward interpretation. The simplification was done by particularizing the general formulation of [1] to a particular class of contact surface parameterization, for rigid body description. This development led to simple expressions of contact forces between particles, both for frictionless and frictional cases. The frictional cases demanded care in updating and saving the time-history variables, when considering a spring-based constitutive modeling to represent the frictional interface law.

Examples are going to be given involving classical simple problems, for benchmarking, as well as more complex examples involving multiple particle interactions. For the case of NURBS-based particles, the present algorithm is limited to convex particles, while for the polyhedral particles, concavities are properly addressed as in [2].

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Conductivity of Rough Contact in Presence of Oxide Films

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The study of electric conductivity of oxidized contact interfaces is crucial for a broad range of technological applications, from electronics to renewable energy systems. Oxidation at contact interfaces can significantly alter the electrical properties of materials, often leading to increased resistance, reduced efficiency, and ultimately affecting the reliability and performance of electronic devices. At small scales, both surface roughness and oxide film repartition and its thickness affect the electrical conductivity thus rendering the problem complex and challenging due to the randomness aspect of both phenomena.

Usually, in the rough contact mechanics community, the thermal and electric conductivity of rough surfaces is analyzed through their equivalence with the normal contact stiffness demonstrated by Barber [1]. However, this analogy is valid only if the true contact area is equivalent to the conductivity area, which is not the case in isolating oxide films. In this work, we analyze the conductivity of rough contact interfaces in the presence of oxide films (see Fig. 1) combining an FFT-BEM solver [2] with an in-house Fast-BEM solver [3] constructed on the concept of Hierarchical matrices and ACA+ low-rank approximation of remote blocks [4].

We demonstrate a link between roughness correlation length, oxide geometrical characteristics and electric resistance using advantages of both FFT-BEM and Fast-BEM solvers and an enhanced data exchange between them. We establish approximate bounds on the variation of the electrical resistance with the oxide film surface ratio.

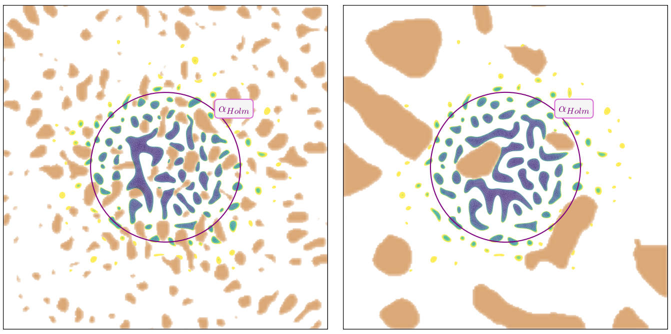

Figure 1: Conductive contact spots and the electric flux of contact interfaces in presence of oxide films obtained for different geometrical oxide characteristics.

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Session 6

Machine Learning Fretting Contact Mechanics—Tractional Torque and Energy Dissipation Forecasting

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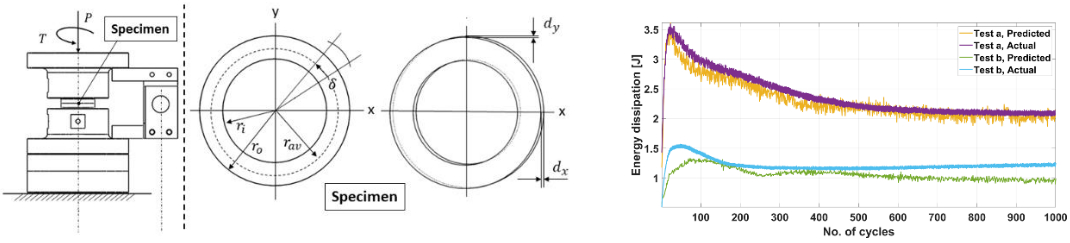
Fretting wear, a phenomenon encountered in various engineering applications poses significant challenges in accurately predicting tractional torque and energy dissipation. Numerical simulations are pivotal in advancing engineering innovations; however, the complexity of the processes involving multiple time and length scales in tribology and particularly fretting make it inconvenient to use numerical prediction. Moreover, none of the models to date relate to a material composition for contact geometry evolution [1], and even a bird-eye view makes the limitations of available wear models and their narrow applicability in fretting contacts visible [2]. Upon it, traditional computational approaches become computationally burdensome when dealing with coupled systems involving multiple scales and physics with distinct timescales, such as third-body wear with excretion of wear debris and evolution of contact geometry in fretting interface; thus, cycle jumps were used by researchers to reduce computational time while performing numerical investigations.



(a) (b)

Figure 1: Frictional energy dissipation in a contact experiencing cyclic loading: (a) experimental configuration for preformed flat-on-flat specimen tests, (b) energy dissipation in fretting tests predicted by machine learning model compared with measured values in tests.

A transfer function is needed to connect material composition and tribo-conditions to contact mechanics and geometry evolution. In an effort to develop a model that can map contact mechanics to material composition, a novel approach utilizing Long Short-term Memory-based neural networks is initially developed to forecast these critical parameters with high confidence. The study employs a powerful sequence modeling technique to analyze historical data collected from fretting contact experiments. The network is trained to capture intricate temporal dependencies, making it well-suited for predicting the tractional torque and energy dissipation within fretting contact interfaces. The model demonstrates its ability to learn and generalize complex fretting behavior. Our investigation results exhibit remarkable accuracy and precision in predicting tractional torque and energy dissipation. The predictions align closely with experimental measurements, indicating the robustness and effectiveness of the proposed approach and the model's versatility and reliability.

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Investigation of frictional resistance in sliding contact between undulating surfaces and third-body particles

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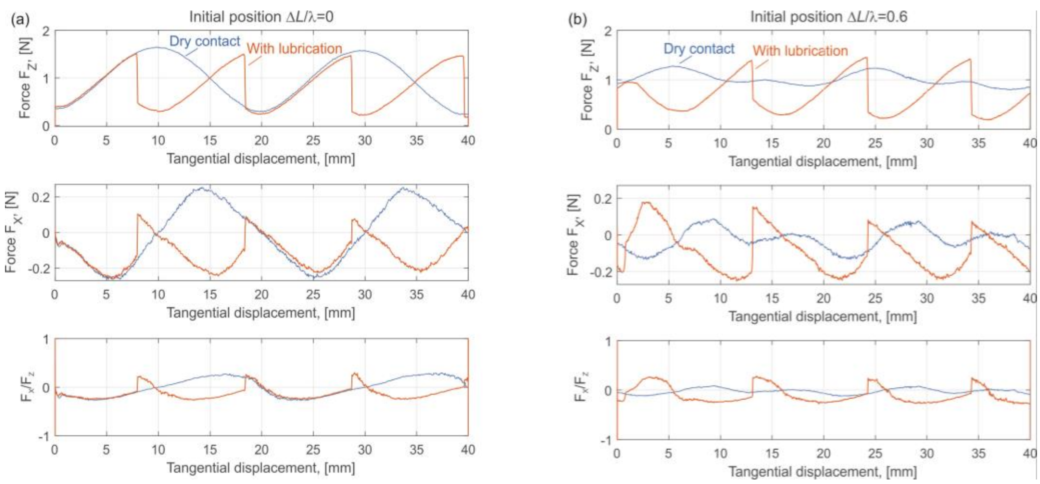
A model system of sliding contact between rough surfaces with third-body particles is experimentally studied. The experiment is designed to isolate the direct contact between first bodies so that friction resistance is induced completely by the interactions between the third-body particle and the wavy surfaces of the rubbers.

In dry contact of s single particle, the particle exhibits pure rolling during the sliding of the first bodies. In this scenario, the normal and tangential forces fluctuate more prominently with larger particles, but the overall macroscopic friction resistance for overcoming sliding doesn't vary with the particle size. Interestingly, this friction resistance is notably affected by the initial alignment of the surface waviness concerning the particle's position, represented by the phase shift between the two waviness patterns of the elastic bodies. The minimum friction resistance occurs when the particle is initially positioned in the valley of the lower surface waviness and contacts the peak of the upper waviness.

Under lubricated conditions, a starkly different behavior is observed. The low local friction at the interface due to the lubrication facilitates the rapid movement of the particle into the valley of the surface waviness upon compression. This abrupt displacement causes the particle to settle into a stable position, necessitating substantial force to push it further (see Figure 1). This process is similar to the well-known Prandtl-Tomlinson model. In this lubricated scenario, the macroscopic friction resistance remains consistent, independent of the initial alignment of waviness, consistently maintaining the highest level observed in dry contact. Consequently, it can be concluded that lubrication increases the macroscopic friction resistance.



(a) (b)

Figure 1: Friction resistance in dry contact and under the condition of lubrication with (a) zero phase shift between two wavy surfaces and (b) (dimensionless) phase shift of 0.6.

Flexoelectric contact mechanics

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Flexoelectric effects can have a significant impact on the mechanical behavior of dielectric bodies in contact at micro/nano and macro scales. In particular, the state of deformation and stresses in the vicinity of the contacting area deviates remarkably from what is predicted by Hertzian contact theory [1]. In the classical theory of elasticity, there is no length scale parameter and no possible electrification for isotropic materials. In this presentation, by using couple stress flexoelectric theory [2,3], we investigate the flexoelectric effect near the contacting area of an isotropic dielectric material pressed by a rigid insulator probe, shown in Figure 1.

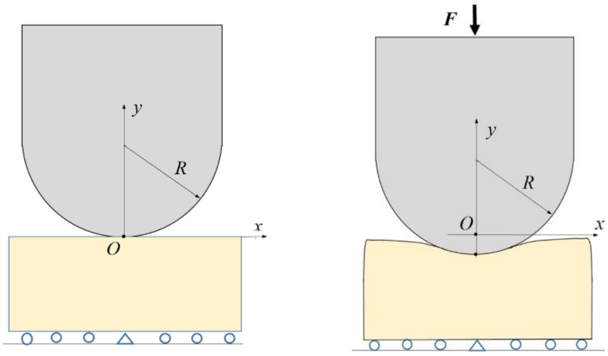

Figure 1: Flexoelectric block pressed by rigid insulator probe: before (left) and after (right) deformation.

This simple model noticeably uncovers the potential role of flexoelectricity in contact mechanics and electrification, where electric polarization may appear as a result of coupling between the electric field and mean curvature vectors and vice versa, even for isotropic, cubic and centrosymmetric dielectric materials.

Since there are no closed form solutions for this size-dependent contact problem, we have developed a boundary element formulation to calculate the electromechanical quantities for two-dimensional isotropic flexoelectric contact problems. The numerical results show interesting characters, which are different from those in classical theory. This investigation shows the importance of flexoelectricity in contact mechanics, where it may explain many unresolved phenomena in tribology.

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Metainterfaces: how to design a rough contact that obeys a specified friction law?

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Many devices, including touchscreens and robotic hands, involve frictional contacts. Optimizing those devices requires fine control of the interface's friction law. We lack systematic methods to create dry contact interfaces whose frictional behaviour satisfies preset specifications. In this talk, I will present a generic surface design strategy to prepare dry rough interfaces that have predefined relationships between normal and friction forces [1]. Such metainterfaces circumvent the usual multiscale challenge of tribology [2], by considering simplified surface topographies as assemblies of spherical asperities. Optimizing the individual asperities' heights enables specific friction laws to be targeted. Through various centimeter-scaled elastomer-glass metainterfaces, I will illustrate different types of achievable friction laws, including linear laws with a specified friction coefficient and unusual non-linear laws. This design strategy represents a scale- and material-independent, chemical-free pathway toward energy-saving and adaptable smart interfaces.

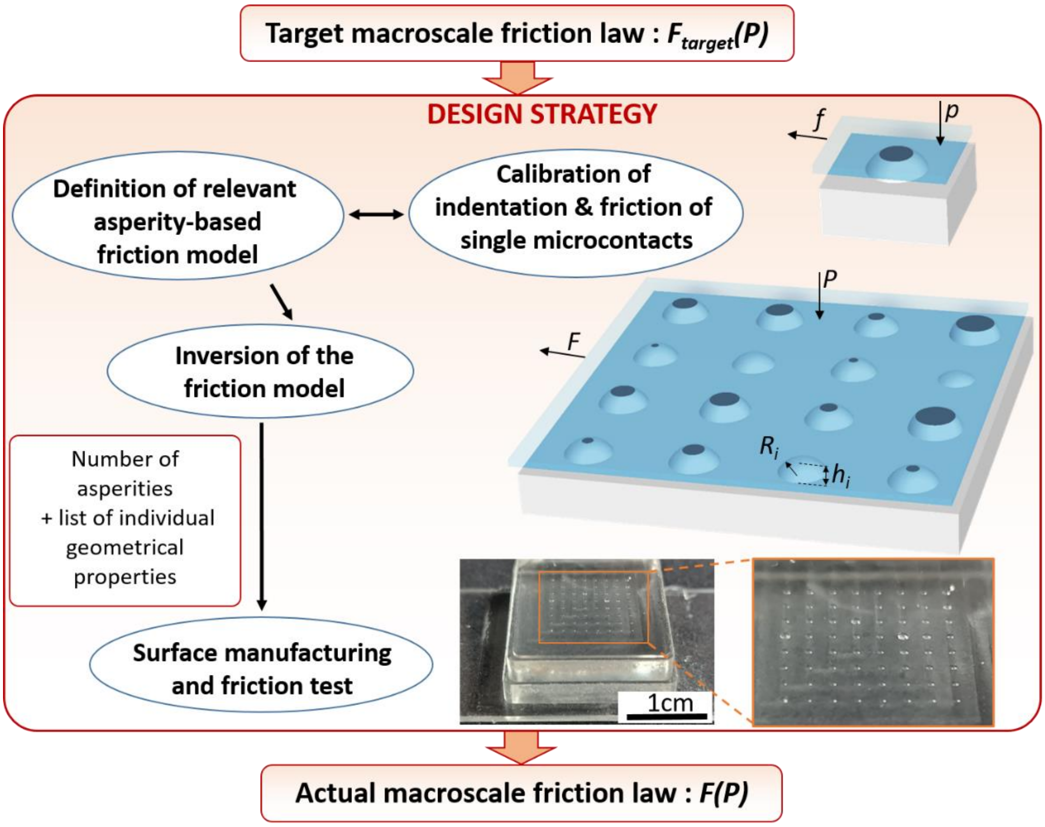

Figure: Flowchart of the design strategy for metainterfaces with specified friction laws [1].

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Frictional contact of soft polymeric shells

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The classical Hertzian contact model establishes a monotonic correlation between contact force and area [1-3]. In this presentation, we demonstrat that the interplay between local friction and structural instability can intentionally lead to unconventional contact behavior when a soft elastic shell makes contact with a flat surface [4]. Deviation from Hertzian contact arises from bending and buckling within the contact area, resulting in a notable change in the contact morphology. Friction affect significantly the mode of deformation and contact relation. Additionally, it introduces hysteresis during loading and unloading. Different contact regimes are discussed in terms of rolling and frictional sliding mechanisms, providing insights for tailoring contact behaviors in soft shells.

Our experiments and numerical simulations show (Figure 1) that a circular contact area is first established and grows by indentation (p0), followed by a smooth transition from circular to disk-like contact as a result of bending in the contact area (p1). As indentation progresses, a secondary transition occurs, resulting in a sharp reduction in the contact area despite increased contact force (p2-p3). We have shown how the interplay between structural instability and the local friction coefficient dictates the morphology of contact. Two transition points are identified in the loading phase, classifying three regimes of deformation: Hertzian, intermediate, and post-buckling. While the contact area increases monotonically in the first two regimes, it abruptly drops and then remains constant in the post-buckling regime. Mechanisms for the evolution of the contact area will be discussed in terms of the distribution of pressure in the contact zone. The interplay between friction, material properties, and structural instability leverages the controlled departure from Hertzian behavior and monotonic contact force-area relation. This new understanding presents a direction to tailor the contact morphology and governing mechanism, offering solutions to a diverse range of engineering applications such as systems with superior damping capabilities, switch haptic, or vesicle manipulation.

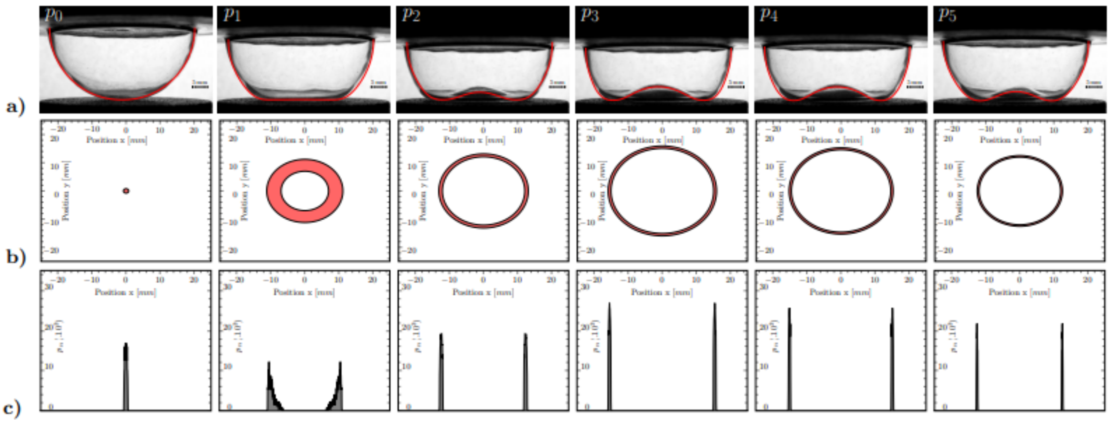

Figure 1 : (a) In-situ snapshots of shell profile indented by a PLA plate, under dry contact (μ = 1.0) at different stages of indentation, corresponding to points p0-p5, marked in Fig. 2a. The profiles obtained from the simulation are superimposed with red solid lines for comparison. (b) and (c) present, respectively, the corresponding contact morphology and the contact pressure distribution (p(x)/E), obtained from simulations multiplied by 103 for clarity. Inset numbers in (b) present the total contact area.

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Keynote 4

Approximation methods for vibro-impact problems: mathematical issues

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The topic of this talk is to give an overview of mathematical issues in the simulation of vibro-impact problems.

More precisely we consider rigid multibody systems subjected to frictionless non-penetration conditions and we model velocity jumps at impacts by Newton's law. From the mathematical point of view the appropriate framework for the generalized accelerations is the space of vector-valued measures and the problem is described by a measure-differential inclusion.

The unilateral constraints due to the non-penetration condition lead to a complex strongly non-linear dynamical behavior and uniqueness or continuity on data is not anymore always satisfied by such systems. As a consequence reliable simulations can not be performed by using a simple adaptation of ODE solvers.

The main difficulties in the approximation of the solutions will be highlighted through several examples. Then the advantages and drawbacks of different kind of algorithms will be discussed.

Session 7

A Method for Multibody Contact Represented by Nonlinear Complementarity Problems

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Multibody dynamics simulations are essential in a variety of applications. Contact and friction problems play a crucial role and continue to present complex challenges. A typical representation of a single contact point using the Coulomb friction model leads to the friction cone (Figure 1 (a)), which introduces two main challenges. The first one is nonlinearity; it originates from the friction force that can have arbitrary orientation in the tangent plane. This results in a nonlinear complementarity problem (NCP). The second one is force coupling, where the bound of the friction force depends on the normal force, which is unknown itself and must be concurrently solved with the friction force.

In practice, two simplifications are often introduced. The first one is to discretize the friction cone such that friction forces are applied only along two independent directions, which eliminates the nonlinearity and leads to the pyramid model (Figure 1(b)). The second one is to replace the friction force bounds determined by the normal force with fixed estimated values, which eliminates the normal-tangential force coupling relations and leads to the cubic model (Figure 1(c)). At this stage, each normal and friction force component at the contact point is treated independently, allowing the use of standard LCP solvers. While these simplifications yield computationally feasible solutions, they introduce errors that conflict with real-world physical behaviors. For instance, friction forces can become inconsistent with the normal force, or velocities can become unnaturally restricted in certain directions. Furthermore, while additional iterations are often introduced to refine the estimated friction force bounds, this approach significantly increases computational costs without ensuring convergence.

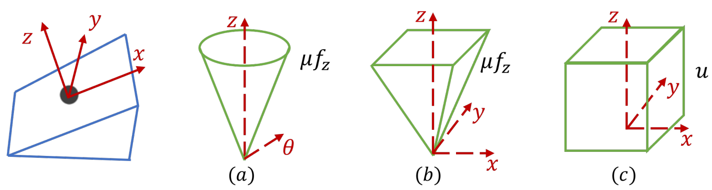

Figure 1: Representations for a contact point (a)cone, (b)pyramid, (c) cubic

In this study, a systematic algorithm is presented for the nonlinear model. It takes a conceptual approach different from existing ones. It first deals with a solvable linear problem and then quantifies and eliminates the errors introduced by the two main simplifications discussed above. Initially, a specific algorithm was developed for the pyramid model. It pivots the entire contact point instead of individual components, resolving complementary problems together with normal-tangential force coupling. Building on this, an iterative framework is further developed that classifies error types in pyramid solutions. It then adjusts pyramid bounds, transforming them into a cone representation. Simulation tests reveal that the proposed algorithm effectively eliminates the simulation errors inherent in conventional methods. Moreover, it substantially reduces computational cost, offering a more realistic and efficient approach for multibody dynamics simulations.

An interior-point approach to solving friction contact problems in hyperstatic scenarios

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We present numerical solutions for solving a mechanical model of one-sided contact problems with Coulomb friction between solid bodies in finite dimension. Discretized in time, the model of interest is as follows:

$$\begin{aligned}
&Mv + f = H^\top r,\\
&Hv + w + se = \tilde{u},\\
&s = \mu\|\tilde{u}_{\mathrm{T}}\|,\\
&\mathcal{K}^* \ni \tilde{u} \perp r \in \mathcal{K}.
\end{aligned} \tag{1}$$

The given data includes the matrices M, H, two vectors f, w and the friction coefficient μ. For a contact variable $x \in \mathbb{R}^3$, the decomposition is denoted as $(x_{\mathrm{N}}, x_{\mathrm{T}})$, where N, T refer to the normal and the tangential components. A generalized velocity v is defined by two relationships linking the reaction force r through the dynamical equation $Mv + f = H^\top r$, and relative velocity u through the kinematic relation $Hv + w = u$. Applying the De Saxcé's transformation $\tilde{u} := u + \mu\|u_{\mathrm{T}}\|e$, with $e = (1,0,0)^\top$, the Coulomb's friction law for only one contact leads to the conic complementarity problem (1), where $\mathcal{K} := \{(r_{\mathrm{N}}, r_{\mathrm{T}}^\top) : \|r_{\mathrm{T}}\| \le \mu r_{\mathrm{N}}\}$ represents the friction cone of reaction force and $\mathcal{K}^*$ is its dual cone.

This model has been introduced by Acary et al. in [1]. They proved that, under mild assumption, a solution always exists. Amongst numerous methods of solving (1), the non-smooth Newton method is one of the most efficient for obtaining high-accuracy solutions when r is uniquely determined. However, it has numerical difficulties in hyperstatic situations (rank deficiency of H), including rigid multi-body systems, robotics, or granular materials. Our study focuses on handling these specific cases.

The interior point algorithm, presented in [2], has efficiently solved the convex relaxation of problem (1), where s is fixed. The algorithm we present here for solving (1) is a natural extension of this method. We show that even when H is rank-deficient, this algorithm is efficient. We present numerical experiments showing that our algorithm provides more accurate solutions than standard first-order methods such as the block-projected Gauss-Seidel method.

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On the penalty method in computational contact mechanics

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The penalty method is widely used method in contact mechanics [1]. (As an example we mention the program package ABAQUS.) This despite the shortcomings of the method, which are evident from a mathematical analysis. First, it is non conforming which has the consequence that the penalty parameter has to be chosen big, in order that the convergence rate is optimal. A high penalisation, however, leads to a ill conditioned discrete linear system. Furthermore, a high penalisation leads to an overrefinement along the boundary when adaptive schemes are used, cf. [2]. However, in the engineering literature the question of how to chose the penalty parameter is not adequately addressed [1]. In our work we investigate these questions. First, we consider the penalty method as a method to enforce Dirichlet boundary conditions, and we show that a high penalty leads to an optimally convergent method.

For the problem of two elastic bodies in contact we show that this cannot happen. We perform both an priori and a posteriori error analysis, and thorough numerical tests, which show that the conflicting requirements for the penalty parameter have the consequence that an optimally convergent method cannot be obtained. As a reference we use the Nitsche method, which can be seen as a consistent variation of the penalty method.

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Session 8

Coupled approach to contact dynamics via the Dirichlet-Neumann Schwarz alternating method

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This work introduces a novel approach for simulating mechanical contact, rooted in the Schwarz alternating method [1]. Originally designed for domain decomposition, this method seems to be well-suited for addressing mechanical contact problems. In a multi-body contact context, the Schwarz alternating method aims to treat each body separately and to prevent interpenetration using an alternating Dirichlet-Neumann iterative process. This approach has a strong theoretical foundation [2], does not require contact constraints, and offers a flexibility making it suitable for multiscale and multiphysics contact problems.

First, a numerical comparative study of the Schwarz contact method to conventional contact strategies [3], such as Lagrange multipliers and penalty approaches, has been performed based on a one-dimensional impact benchmark. This study highlights the substantially better accuracy for various quantities of interest (i.e., impact/release times, contact positions, velocities, forces, kinetic and potential energies), and remarkable total energy conservation of the Schwarz methodology compared to conventional contact algorithms.

Numerical solution of the dynamic contact problems is known to give rise to instabilities and artificial oscillations in some quantities of interest. The presence of such numerical artefacts has been revealed in contact velocities and forces using the Schwarz contact method. To address this issue, we introduce an effective solution based on the so-called naive-stabilized approach. This approach aims to eliminate the inertia of the contact boundary by making the acceleration on the contact boundary vanish. Applicable to both explicit and implicit time integrators, this technique significantly reduces artificial oscillations while maintaining the accuracy, energy conservation, and efficiency of the Schwarz contact algorithm.

We then extend the Schwarz contact approach to a multidimensional context, and demonstrate its efficiency and accuracy in handling contact on a 3D impact problem. The study showcases the method's natural ability to use different time integrators, time steps, mesh topologies, and mesh sizes in different domains involved into contact. This is a significant advantage rarely afforded by conventional contact methods. In a multidimesional scenario, we propose a reliable strategy for the construction of ransfer operators for information exchange between different time steps and non-matching meshes.

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Bridging macroscopic and microscopic contact interaction using a multiscale variational formulation based on surface and volume homogenisation

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Contact interaction is inherently a multiscale problem due to surface roughness in the boundary of solid bodies. Classically, at the macroscale, contacting surfaces are nominally smooth and are characterised by non-penetration and Coulomb's friction constraints. Alternatively, the observed macroscopic contact response can be interpreted as the manifestation of the real contact interaction occurring at the microscopic roughness level. In this scenario, the macroscopic contact behaviour is not defined *a priori* but emerges from the fully resolved microscopic contact interaction. In turn, the microscopic contact is driven by the downscaled displacement and deformation of the macroscopic contact surface.

Leveraging the recent multiscale modelling paradigm called Method of Multiscale Virtual Power (MMVP) [1], this work contributes with a formal derivation and computer implementation of multiscale contact models, specifically designed towards applications with surface roughness where one of the sides is rigid. The framework provided by the MMVP fundamentally relies on the postulate of kinematical insertion and homogenisation operators, and the identification of a suitable form for the variational statement of the Principle of Multiscale Virtual Power (PMVP), such that all other ingredients in the formulation appear as natural consequences of the initial options. Due to the particular form of the contact constraints, several aspects of the MMVP need to be properly adapted to prevent spurious tractions at the microscopic contact boundary, which come at the cost of an outer iteration to the equilibrium problem. Two families of models are derived, distinguished by the application of surface or volume-based deformation kinematics and subsequent homogenisation operators. These two classes and the main approaches in the literature are critically compared concerning the global characteristics of the microscopic deformation, convergence with the dimensions of the microscopic domain, and computational cost [2,3].

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Keynote 5

On the modeling challenges in large-deformation rubber contact

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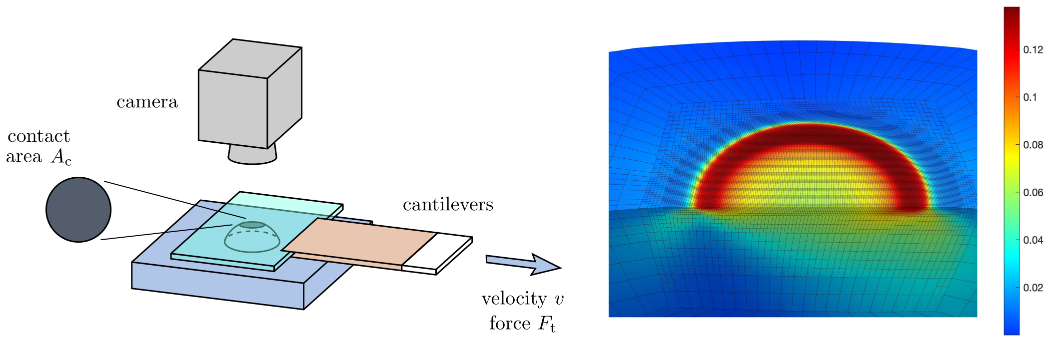
The modeling of contact and friction of rubber poses various challenges, both theoretically and numerically. They stem from the nonlinear material behavior of rubber under large deformations that is characterized by incompressibility, entropic elasticity and viscoelasticity. Beyond that there is the challenging contact behavior, characterized by Tresca friction, adhesion and surface wrinkling. The latter can lead to self-contact and partial lift-off, as in the case of Schallamach waves.

This work discusses computational strategies for handling these challenges focusing on quasi-static problems. The strategies are exemplified on the sliding cap problem shown in Figure 1a. A finite element formulation is presented that is capable of handling the



(a) (b)

Figure 1: Large-deformation contact of a sliding rubber cap: (a) Experimental setup [1] (b) Computed shear tractions during the transition from sticking to sliding (in units of Young's modulus).

challenges posed by the material and contact behavior, see Figure 1b. In particular, approaches for accurately regularizing the adhesion, friction and wrinkling behavior are presented based on the theoretical and computational models of Mergel et al. [1, 2] and Lengiewicz et al. [3]. The approaches benefit from the local enrichment of the contact discretization [4].

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Session 9

Modelling mechanical contact between solids within Eulerian framework

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Figure 1: Developement of Von Mises stresses for evolving deformable solids in contact. From the initial configuration, the disk is grown to introduce contact and, ultimately, stress, showcasing the applicability of our method to geometrically more intricate domains. Evolution from left to right, from a stress-free to a stressed system.

Solid-solid mechanical contact is predominantly modelled within Lagrangian frameworks, which, despite their extensive development and successful application to various contact scenarios, often necessitate intricate algorithms for contact detection and resolution. The complexity escalates significantly when dealing with evolving boundaries, as observed in systems where materials undergo growth within constrained spaces. In this study, we present a comprehensive Eulerian finite-element framework tailored for modelling contact between elastic solids, specifically addressing challenges associated with evolving and intricate surfaces [1].

Our approach employs an Eulerian perspective and incorporates a phase-field method, offering a diffuse representation of geometries on a fixed mesh to facilitate the modelling of surfaces undergoing evolution. The methodology introduces an innovative volumetric contact constraint utilizing penalty body forces, efficiently addressing the interpenetration of solids. To model elasticity, we make use of the reference map technique [2]. We demonstrate the validity and versatility of our method through numerical examples, emphasizing its capability to accurately depict intricate solid-solid interactions. The Eulerian phase-field formulation streamlines contact detection and resolution processes.

Moreover, our framework seamlessly integrates with other physical phenomena by incorporating multiple energy terms into the phase-field evolution. This enables the modelling of multiphysics scenarios, presenting a valuable tool for a diverse range of applications involving chemically or physically evolving deformable solids in contact (see Fig 1). This is particularly relevant in processes like the deterioration of porous media, where such interactions commonly occur.

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Nonlinear solvers for poromechanics with fracture contact mechanics

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Fluid flow in a fractured porous media is a highly complex multi-physics problem, with tightly coupled mechanical, hydraulic and thermal processes. In the porous media group at University of Bergen, Department of Mathematics, a mathematical model for flow in fractured porous media has been developed, which fully incorporates the coupled nature of the physical processes [1]. This includes modeling the deformation of fractures by contact mechanics, and the model also considers the enhancement of fracture permeability due to shear dilation of the fractures. This last point is particularly relevant in the context of enhanced geothermal systems.

The mathematical model is solved numerically using our in-house simulator PorePy [2], which is specifically tailored for simulating processes in fractured porous media. After discretization, the resulting nonlinear system is solved by a semi-smooth Newton scheme, taking into account that the contact mechanics equations are not differentiable everywhere. This Newton solver lacks robustness, however, and many simulation setups have been identified for which the solver fails to converge**.** We are therefore looking into alternative nonlinear solvers that can provide additional robustness.

The contact mechanics equations are often a source of difficulty for the nonlinear solver, due to their nonlinear and nonsmooth nature. These equations also gain an additional complexity by the inclusion of shear dilation, which introduces a highly nonlinear relationship between flow and mechanics in the fractures. Hence, we are considering several alternative solvers which are based on regularizing the contact equations. These include Uzawa-type solvers and Quasi-Newton solvers, inspired by the algorithms presented in [3,4] among other works. Work is also being done on identifying the problematic parts of the system for individual setups, and using this as a guide to choose the appropriate nonlinear solver.

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Two ‘game-changers’ in development of FETI-based algorithms for large contact problems

The current development of supercomputers motivated the research of massively parallel algorithms to solve many challenging problems, including huge contact problems of elasticity. Here, we describe two recent contributions that considerably increase the dimension of solvable problems and improve the convergence rate of existing algorithms.

The first contribution exploits the three-level hybrid domain decomposition method proposed by Klawonn and Rheinbach [1] to solve multibody contact problems with billions of nodal variables. The basic idea is to decompose the domains occupied by the bodies into subdomains as proposed by Farhat and Roux, use the transformation of variables to join some subdomains by the rigid body motion of adjacent faces into clusters [1], and then use the standard FETI/BETI methodology to get well conditioned dual quadratic programming problems with bound and equality problem which can be solved with an asymptotically optimal (linear complexity).

The second contribution concerns improving the rate of convergence of the SMALBE and SMALSE algorithms by adaptive reorthogonalization of constraints [6, 7].

We report both the theoretical results and the results of numerical experiments. The results of numerical experiments [2]–[5] show the considerable scope of scalability of both H-TFETI and H-TBETI and indicate that this method can be helpful for the solution of huge linear and contact problems. Moreover, the two-level structure of the coarse grids (split between the primal and dual variables) can be effectively exploited by the node-core design of the modern supercomputers’ hardware.

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Coupling adhesion and sliding friction within a mortar-based contact discretisation through a primal-dual active set strategy

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Adhesion research in contact mechanics, rooted in the 1970s with the cornerstone analytical models JKR and DMT, has gained renewed significance due to advances in complex engineering systems. Biomedical devices such as human joint prostheses, coatings for optimal adhesive-friction conditions in aerospace and electronic sectors, and wafer bonding in the microelectronics industry are some representative examples. Adhesion also plays a pivotal role in friction and wear theories, thus being a fundamental aspect for the analysis of tire-road interaction and the design of bearing systems. For these reasons, there is an increasing need for specialized computational tools that can model such phenomena, which is reflected in the intense research activity on the topic in recent years [1].

In the present contribution, we consider the Raous, Cangémi and Cocou (RCC) model which has prevailed within the community as a sound model for adhesion coupled with sliding friction [2]. This model follows Frémond's approach, introducing the concept of *intensity of adhesion* as a damage-like state variable. This variable provides a macroscopic description of the various microscopic bonds distributed over the interface. The resulting model consists of a set of constraints for unilateral contact and Coulomb friction, that allow adhesive effects upon separation, along with an ordinary differential equation that governs the viscous evolution of the intensity of adhesion.

This research explores the numerical treatment of the RCC model within the well-established dual-mortar contact framework. The boundary non-linearities resulting from the nodal lumped contact constraints are treated using a prima-dual active strategy [3]. By modifying the classical non-linear complementary functions to encompass the adhesive terms, a semi-smooth algorithm is obtained that allows the incorporation of the active set search in the solution loop, as well as the evolution of the adhesive tractions. This work also extends the kinematical variables typically found in mortar-based discretisations of the contact constraints, towards an appropriate computation of the adhesive terms. Finally, different numerical examples, illustrating the various adhesive contact scenarios, are used to evaluate the validity of the developed framework.

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Session 10

An Improved Normal Compliance Method for Non-Smooth Contact Dynamics

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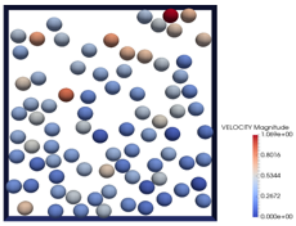
Abstract: Based on the growing importance of understanding granular media and their behaviors in various industries, this work proposes a new method different from the Discrete Element Method (DEM) [1] and the Non-Smooth Contact Dynamics (NSCD) [2] approach to model granular dynamics. We focus on a discontinuous Moreau second-order sweeping process for modeling contact dynamics, incorporating the Moreau-Yosida regularization [3] with parameter α to develop a regular contact model. We propose the Improved Normal Compliance (INC) method to ensure energy conservation and employ a combination of the Newmark method [4] and Primal-Dual Active Set (PDAS) [5] to address nonlinearity. The main aim of the present work is to improve an implicit regularization method for which energy conservation and non-penetration are quite similar to NSCD-NLGS along with a suitable computational cost. Several numerical experiments are reported for verification and validation purposes, and also to evaluate the efficiency and assess the performances of Newmark-PDAS-INC method compared to other numerical methods (DEM, NSCD-NLGS).

For example, figure 1 gives some numerical results concerning a two-dimensional system with 81 particles. Each particle has a random trajectory and velocity with respect to time without friction and without gravity.



$\Delta t = 10^{-4}$	Energy	Error	Penetration
DEM	16.7219349	$1.4866 \times 10^{+1}$	1.4798×10^{-2}
NSCD	6.7248957	4.8171×10^{-8}	3.2928×10^{-4}
INC ($\alpha = 2$)	6.6738305	7.5935×10^{-3}	8.8043×10^{-3}
INC ($\alpha = 3$)	6.7248927	4.8092×10^{-7}	6.4869×10^{-2}

Figure 1: 81 particles and numerical comparison bewteen different methods.

It turns out that the INC method implemented are at least just as much relevant as the NSCD-NLGS method and much better than DEM, regarding energy conservation properties and non penetrations, as they display physically realistic behaviour.

In this work, we will propose different simulations including the restitution coefficient and the friction, and we will make comparisons between the NSCD, DEM, INC methods focusing on energy conservation, penetration and CPU time.

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Experimental investigation of a sphere on plane contact using In Situ X-ray Computed Tomography

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Nowadays, to study in-situ or in operando the contact and friction behavior of an interface, measurements are mostly made through optical devices which requires the use of at least one optically transparent material and limit the analysis to only the evolution of the interface and more specially to the real contact area. Thus information outside this confined zone are most of time inaccessible. In this study, we overcame these two limits by using an X-ray Computed Tomography (XRCT). Starting from the very few pioneering studies, we adopted a more model approach to investigate by XRCT the classical laws of contact mechanics in a model sphere on plane contact. Our main objective was to examine the relationship between loading conditions, material properties, contact area and bulk deformation in 3D.

Thanks to an experimental loading device installed in a laboratory tomograph [1], we were able to obtain 3D images (Figure 1) of a contact between a smooth PDMS sphere against a smooth PMMA plane for different loading conditions: pure normal loading/unloading (indentation) and shear loading under constant normal force (friction test). First, after segmentation of the 3D volumes, we extracted the evolution of real contact area and the surface displacement field of the PDMS specimen as function of the loading conditions (for indentation and friction tests). We then compared these evolutions to established experimental results [2] and to the classical theoretical models of contact mechanics [3]. Finally, we performed Digital Volume Correlation analysis by analyzing the displacement of dispersed particles that were inserted inside the PDMS sphere. We, thus, measured the 3D bulk displacement, strain and stress fields (Figure 1) and compared them again with the prediction of theoretical models.

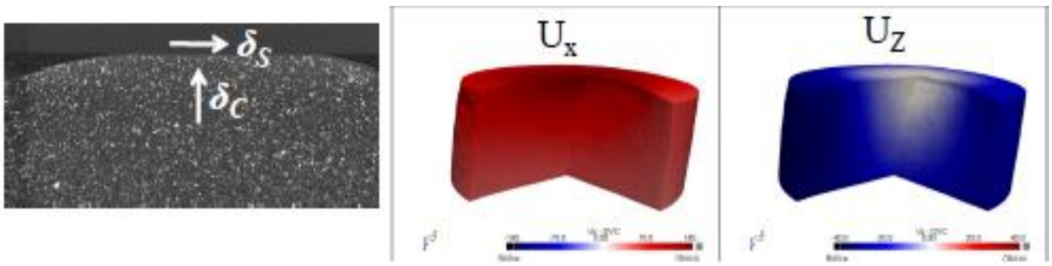

Figure 1: Left: slices of a reconstructed volumes of a seeded sphere in contact with a PMMA plane after a compressing displacement (δc = 280 µm) and a shear displacement (δs = 1650 µm). Right: measured displacement field through DVC.

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Mortar-type finite element formulations for mixed-dimensional beam-to-solid contact interaction

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The contact interaction of rod- or beam like structures with three-dimensional (3D) continua (solids) can be found in a variety of different physical problems ranging from classical engineering problems (e.g., belt drives) to biomedical applications (e.g., stents for aortic aneurysm repair). An efficient and accurate modeling approach for the rods or beams is to employ structural beam theories, which reduce the 3D beam continuum to a one-dimensional (1D) curve embedded in 3D space. Employing these 1D beam models in beam-to-solid contact problems requires the development of contact formulations between the 1D beam structures and the 3D solid continuum, i.e., a mixed-dimensional contact formulation.

In the context of the employed finite element method, the considered mixed-dimensional contact problem requires suitable contact schemes between the inevitably non-matching grids of the beam centerline and the solid surface. From a geometric point of view, unilateral contact between 1D beams and 3D bodies can be described as a line-to-surface (1D-2D) contact problem, where the 2D surface is the boundary of the solid volume. For the discretization and solution of this challenging problem existing techniques from 2D-2D surface-to-surface contact [1], 1D-1D beam-to-beam contact [2] and 1D-3D mixed-dimensional coupling [3], are enhanced and combined.

Among the topics addressed are the different types of contact discretization schemes, e.g., mortar-type and Gauss-point-to-segment approaches, with a particular emphasis placed on the mortar-type formulation. Additionally, strategies for constraint enforcement, and robust numerical integration and segmentation are discussed. To round of the talk, a number of different qualitative and quantitative numerical examples are presented in order to underline the usability of the proposed mixed-dimensional contact schemes for academic and practical applications.

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Third medium contact formulation for modeling of pneumatically actuated metamaterials

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Pattern-transforming metamaterials, such as 2D polymer sheets perforated by periodically repeating voids, allow for switchable behavior and novel mechanical properties, e.g., negative Poisson ratio. Their complex response is enabled by local buckling, which can be triggered by either an external load or pneumatic actuation. In both cases, the post-bifurcation response frequently exhibits geometrically nonlinear deformation with self-contact. To design such microstructures, a robust simulation method encompassing the above-mentioned phenomena is thus required.

A third medium method, which relies on a finite element mesh in the microstructural voids, is well suited for the task since it allows the incorporation of both contact and pneumatic actuation, which is particularly appealing to topology optimization problems. A similar concept has been recently used in a soft robotics application by Caasenbrood et al. [1]. The third medium method enforces contact through a virtual material introduced in the gap between contacting surfaces developed to prevent penetration without significantly impacting the solution [2]. Its main advantage is the simplicity of identification of contact surfaces, whereas disadvantages include computational expense and the need to handle possible numerical instabilities of the third medium. Recent progress in the third medium contact for topology optimization has been made by Bluhm et al. [3] and Frederiksen et al. [4].

Here, we present a hyperelastic material model for a third medium handling both contact and pneumatic actuation. Our model relies on penalizing curvature within the third medium elements to stabilize the solution. It can effectively capture contact behavior both in enclosed voids and on open-air surfaces. Compared to the recent methods cited above, our model is more robust, less sensitive to material parameters, and precise in describing pneumatic actuation. We showcase the performance of our model using several simulations of pattern-forming metamaterials.

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Keynote 6

Exploiting viscoelasticity for improved adhesive performance of soft interfaces

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Soft viscoelastic materials are ubiquitous in every-day applications such as seals, tire-road contact, grippers and manipulators, pressure-sensitive adhesives, rubber supports and dampers. Elastomers, silicones and rubbers exhibit a time-dependent material behavior. A better understanding of the contact response is of utmost importance to deal with the current technology challenges, which require robust and efficient engineering solutions in the push towards a carbon neutral society. Although the time and temperature dependence of the material response poses challenges in the material modelling, these peculiarities also offer a large playground for exploiting the material response in order to obtain the desired behavior. Adhesion and detachment in soft contacts may be seen as a problem of viscoelastic crack propagation or healing. During the talk we will introduce our current understanding of how the apparent surface changes as a function of the crack tip velocity in a semi-infinite solid by presenting the two major approaches proposed in the literature: (i) Greenwood theory [1] which, based on the results of Schapery [2], describes the processes happening at the crack tip through a cohesive zone model, (ii) Persson and Brener theory [3] which instead is based on energetic arguments. We will show that although they approach the problem from two different perspectives their conclusions are very similar, in particular giving at very large velocity the apparent interfacial energy is enhanced by a factor equal to the ratio between the glassy and the rubbery modulus, which for real polymers is easily in the range of 10^3. Despite these theoretical predictions have been confirmed by several numerical simulations [3, 4], technical applications exploiting the possibility to tune adhesion over a so large range are scarce. Nevertheless, recent theoretical and numerical findings are trying to clarify how the indenter geometry, the thickness of the substrate, the loading and unloading velocity, the excitation frequency may be exploited to regulate interfacial adherence. Some examples will be presented where an optimal choice of contact geometry and loading/unloading protocol have led to a precise tuning of the adherence force resulting in a new strategy to control contact interactions. Furthermore, still unexplored, possibilities to regulate interfacial adhesion will be discussed considering also the possible limitations that may obstruct their transition to technological applications.

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Session 11

A new Moreau–Jean scheme that guarantees dissipativity

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It is well-known that the classical Moreau–Jean scheme that discretises the Coulomb friction model with Newton's law of impact can generate energy in certain circumstances. By using Frémond's law of impact and friction, we arrive at a numerical scheme that is guaranteed to always dissipate energy.

Introduction

Coulomb's friction model, combined with Newton's law of impact, are widely used in contact mechanics problems. However, it has been well-known since the 1980s [1] that the typical continuous-time treatment of this model, where the sliding direction after impact determines the sign of the percussion, is inconsistent. As such, the Moreau–Jean scheme [2, 3] which discretises this model can generate energy in cases where the direction of sliding changes over a time step.
Experimental evidence provided by Chollet [4] and Frémond [5] has confirmed that the Coulomb friction cone clearly appears when measuring the percussions (demonstrating that the basic model is sound), but that the correct kinematic variable to consider is not the velocity after the impact, but the average of the velocity before and after impact.
We thus adopt this model of impact, and demonstrate that the continuous-time version of this model is consistent and is guaranteed to always dissipate energy in cases of impact and sliding. We then propose the Moreau–Jean–Frémond scheme for discretisation, and demonstrate that the dissipative properties also hold in discrete time. Finally, we present some numerical examples to demonstrate the advantages of our scheme is practice.

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A novel comprehensive energy approach for viscoelastic adhesive contact mechanics

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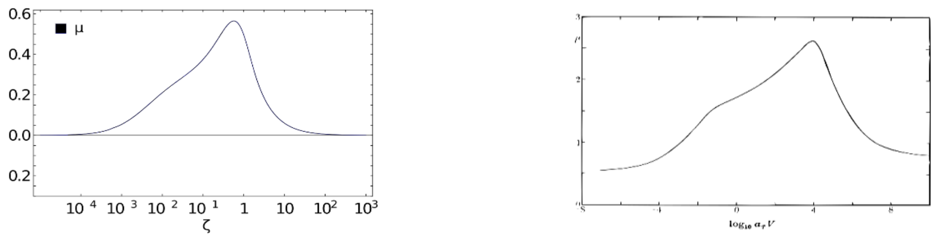
A comprehensive theory of viscoelastic-adhesive contact mechanics is nowadays still lacking. Indeed, most of the existing theoretical and numerical approaches can formulate the closure equations, needed to predict the unknown contact domain, only in adhesiveless or purely elastic conditions. Nevertheless, several experimental data from the literature highlight how adhesion and viscoelasticity might interact each other, strongly affecting the contact behavior [1, 2]. We recently developed a novel energy theory to study the rough adhesive contact of viscoelastic materials in steady-state sliding [3, 4]. Exploiting the boundary element methodology, we derived the energy closure equations by enforcing the balance between the work of internal stresses and the work of adhesion at virtual infinitesimal variations of the contact domain. We calculated the internal work as the sum of elastic energy variation and non-conservative work contribution, the latter arising from the material's viscoelasticity and directly related to the odd part of the viscoelastic Green's function. We found that viscoelasticity may enhance the adhesive performance depending on the sliding velocity, thus leading to larger contact area and pull-off force compared to the equivalent adhesive elastic case, in agreement with experimental results [1]. Also the friction coefficient vs. sliding velocity is a similar fashion to Grosch's experimental results [2] (see figure below). This exhibits a hump at low velocity and a large peak at higher velocity, both resulting from the interplay between viscoelasticity and adhesion. Specifically, at low velocity, the bulk material behaves almost elastically, and friction is mainly originated from the small-scale viscoelastic hysteresis induced by the adhesive neck close to the contact edge. At higher velocity, the effect of bulk (i.e., large-scale) viscoelasticity leads to even higher friction, which we found significantly increased compared to the corresponding adhesiveless case. We also find that independent estimates of friction arising from adhesive hysteresis and bulk viscoelasticity does not provide a correct description of the over frictional behavior of the interface, not even qualitatively.



(a) (b)

Figure 1: The friction coefficient vs. sliding velocity trend, qualitative comparison between (a) theoretical prediction [3-4] and (b) experimental measurements from the literature [2].

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Use of a Waveguide for contact area measurement in synthetic finger development

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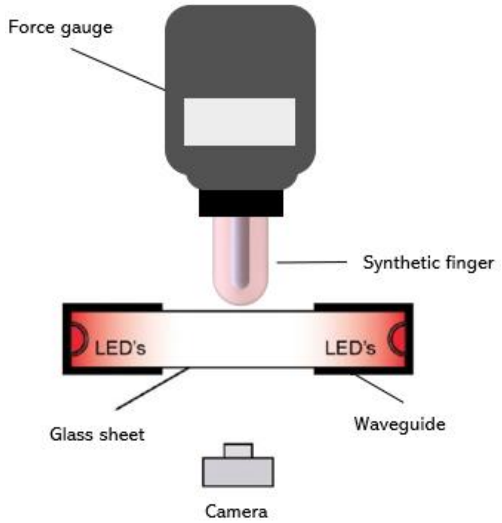
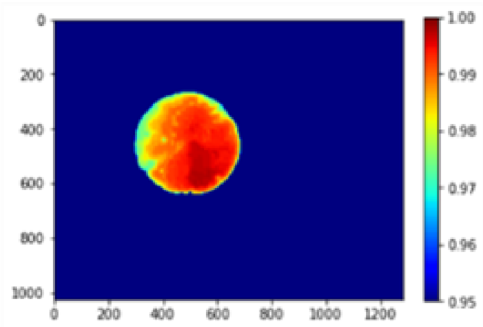
This talk presents some recent research on synthetic finger development, with a particular focus on methods of contact area measurement.

Investigating synthetic fingers made from different silicone materials, this study examines stiffness, deformation, and contact mechanics. This examination is required to mimic human-like touch and grasp in synthetic systems effectively. The methodology includes quasi-static loading tests using a waveguide system, in order to better understand the interaction dynamics under various load conditions.

The Waveguide contact area measurements were used for comparison with an FEA model and Hertzian predictions.



(a)



(b)

Figure 1: Waveguide contact measurement method: (a) schematic of the experiment; force-displacement rig, synthetic finger sample and Waveguide, (b) post-processed result of contact area measurement.

Figure 1 shows the waveguide device, which operates on the principle of frustrated total internal reflection [1]. This device consists of LED lights wrapped perimetrically around the edges of a 6mm thick transparent glass sheet. The contact imaging technique capitalizes on the refractive index difference between air and the transparent plate, enabling total internal refraction. Upon contact with the waveguide surface, the light refracts and scatters, getting frustrated in the opposite direction where it is captured by a Raspberry Pi camera. The subsequent images, recorded at 30 Hz, are analysed using Python. Specifically, the bright areas indicating contact regions between the object and the surface are identified, with their pixel count recorded, allowing for the calculation of contact area percentages.

Ultimately the results of material response could be used in the programming of a robotic grasper.

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Ultra-low friction analysis in soft contact lenses using a dynamic oscillating tribometer

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Friction coefficient is considered as a measurement for clinical comfort of soft contact lenses (SCLs). The comfort of soft contact lenses is affected by many factors, including those related to the patients and to contact lens material. This study aims to evaluate the friction at the soft contact lens-eyelid contact. In order to evaluate precisely the ultra-low friction at this contact, an original technique developed at the Laboratory of Tribology and System Dynamics (LTDS), called "Dynamic Oscillating Tribometer" [1], is used. A variety of soft contact lenses materials is tested in contact with a flat surface made of polyethylene terephthalate (PET) material with saline solution with and without hyaluronic acid under different physiological conditions.

The "Dynamic Oscillating Tribometer", presented in Figure1, consists of a pin-on-plane contact. This tribometer is based on a single-degree-of-freedom mass-spring oscillator system supporting the sliding contact. This apparatus allows us to measure the dynamic free responses at the contact between the SCL and PET lubricated with a physiological solution. The friction is analyzed from the decaying envelope of the free response [1,2]. Using a pseudo-polynomial friction law, the different friction contributions are identified by solving the non-linear equation of motion [3].

The experiments are performed at room temperature with applied normal loads between 50 and 250 mN and sliding velocities varying from 0 to 230 mm/s [4]. The sliding speed corresponds to the blinking speed when closing and opening the eyelid. The applied normal load corresponds to the contact pressure of the eyelid on the cornea.

This research shows the feasibility of measuring friction at the eyelid-lens contact using the oscillating dynamic tribometer. The results have demonstrated that the precision is very high for low friction coefficient. The friction coefficient measurements of the different soft contact lenses at a range of physiological conditions are compared to the results found in literature.

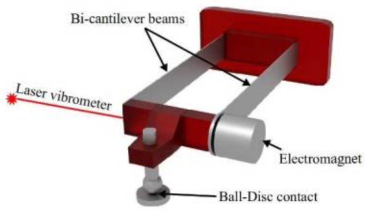

Figure 1: Schematic representation of the Dynamic Oscillating Tribometer.

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