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ScienceDirect
Comput. Methods Appl. Mech. Engrg. 334 (2018) 208–237
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

A catching-up algorithm for multibody dynamics with impacts and dry friction

Alexandre Charles[a,b,*], Fabien Casenave[a], Christoph Glocker[b]

[a] *Safran, Rue des Jeunes Bois, Châteaufort CS 80112 - 78772 Magny-les-Hameaux Cedex, France*
[b] *ETH Zürich, Institute for Mechanical Systems, Tannenstrasse 3, 8092 Zürich, Switzerland,*

Received 29 August 2017; received in revised form 26 January 2018; accepted 30 January 2018
Available online 7 February 2018

Abstract

In the beginning of the 80s, a rigorous mathematical framework was developed for the dynamics of multibody systems with perfect unilateral contacts, particularly due to the contributions of Schatzman and Moreau. Efficient numerical methods have been proposed, for instance Moreau's NonSmooth Contact Dynamics (NSCD) (Moreau, 1999), which was then extended by Jean to cases with friction (Jean, 1999). But the algorithm, in the latter case, is no longer the time discretization of an evolution problem. In this work, we derive a new algorithm from the time discretization of an evolution problem for multibody dynamics with contacts and friction. Our algorithm has many points in common with the one of Jean and Moreau, but it converges reliably and fixes some energetic inconsistencies. The similarities and differences between the algorithms are illustrated on three planar archetypal examples.
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MSC: 00-01; 99-00

Keywords: Time-stepping scheme; NonSmooth Contact Dynamics; Impact; Dry friction; Painlevé's paradox; Kane's paradox

1. Introduction

The NonSmooth Contact Dynamics (NSCD) procedure, developed by Jean and Moreau [1–3], is an algorithm designed to deal with collections of packed bodies and implemented in LMGC90 [4], SICONOS [5] and other softwares. The NonLinear Gauss–Seidel (NLGS) algorithm is the generic solver for the incremental problem arising from the NSCD. The advantage of the NCSD approach is the possibility to solve numerous simultaneous contacts in one time step. This allows large time increments to be used, contrary to the Molecular Dynamics approach [6], where time steps are bounded by the time between collisions. However, NSCD-NLGS has two drawbacks [7]. The first one

* Corresponding author at: Safran, Rue des Jeunes Bois, Châteaufort CS 80112 - 78772 Magny-les-Hameaux Cedex, France.
E-mail address: alexandre.charles@safrangroup.com (A. Charles).

https://doi.org/10.1016/j.cma.2018.01.054
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is related to a formulation of constraints introduced by Moreau [1] on the velocity level for the noninterpenetration conditions. This formulation is exact for time continuous modeling but may generate parasitic interpenetrations in a numerical scheme. Recent attempts to overcome this difficulty can be found in [8,9] where the authors have introduced modifications of the time-stepping discretization scheme. The second drawback of NSCD is the slow convergence of the NLGS algorithm and even the absence of convergence in some cases. The present paper deals with this second topic, which is usually related to the indetermination generated by self-equilibrated force networks in strongly confined granulates [10,11]. In fact, the convergence of NLGS is not guaranteed even for systems with a very small number of degrees of freedom because the NSCD procedure relies on the resolution of an ill-posed problem at each time step. This is known as Painlevé's paradox, and many examples can be found in the literature[1] [7,11–15]. In other words, this numerical convergence problem is related to the properties of the evolution problem that the algorithm is trying to compute. In order to improve the convergence of the NLGS solver, we have to either adapt the solver to the ill-posedness of the problem, for example with regularization techniques as in [7], or to reformulate the evolution problem in order to get a well-posed problem at each time step. The last strategy is the one adopted in this work.

To present this strategy, we need to briefly review the theoretical statement of the evolution problem for nonsmooth systems. We will point out that the described numerical difficulties for multibody systems with unilateral contacts and dry friction are the echo of open questions about the evolution problem.

Until the late 1970s, the usual practice in rigid body dynamics with contact and friction was to write a collection of ordinary differential equations to replace the differential inequations. One was supposed to switch from one differential equation to another using so called discrete equations according to the status (contact or not) of the unilateral constraints. This point of view is referred to as event-driven (this terminology seems to be due to Moreau) in this paper, but the idioms "hybrid systems", "discrete element method" or "molecular dynamics" are also frequently encountered in the literature. The event-driven point of view is convenient neither for theoretical investigations nor for computational purposes because it gives a peculiar status to the instant of impacts in the formulation despite these being unknown of the problems. A new strategy emerged at the end of the 1970s: Schatzman has [16] formulated a global (with respect to the time) evolution problem governing the frictionless bouncing of a point particle against some obstacle. Her formulation was the first one to encompass the episodes of smooth motion as well as the impacts. However, the problem was no longer governed by an ordinary differential equation, but by something more complicated involving extensive use of measure theory (in this framework, the percussion, that is the instantaneous reaction force exerted by the obstacle during a collision is represented by a Dirac measure with respect to time). The paper of Schatzman [16] was restricted to the (frictionless) dynamic motion of a point particle (or a finite collection of such points). It was rapidly extended by Moreau [17] to include cases with dynamic motion of a finite collection of rigid bodies satisfying frictionless noninterpenetration conditions and possibly bouncing against a finite number of (frictionless) fixed external obstacles. The formulation of Moreau suitably modifies the classical Lagrange equations governing the dynamic motion of a finite collection of rigid bodies and allows Lagrange's generalized acceleration to be a measure (with respect to the time) in the line of the setting of Schatzman for point particles. In particular, the reaction force involved in Moreau's formulation of frictionless unilateral dynamics is a generalized reaction force, consistent with the Lagrangian framework. The work of Moreau [17] has made clear how to consistently formulate the frictionless unilateral dynamics of a finite collection of rigid bodies with enough generality to encompass any practical situation raised by engineering applications. This opened the way to numerous theoretical investigations on frictionless multibody dynamics [see 18, for a history of theoretical investigations]. This also leads to the NSCD procedure, a time-stepping (in opposition to event-driven) numerical strategy first introduced by Moreau for the modeling of granular media [17].

Since then, Jean and Moreau [1,2,19] have extended the NSCD procedure to the frictional case (see the top right-hand corner of Fig. 1). Nevertheless, the resulting algorithm is not the discretization of a continuous in time evolution problem. In this context, the Jean and Moreau algorithm is the model itself. In the present paper, this approach will be referred to as numerical modeling. This choice was accepted by Moreau, in the context of the modeling of granular media, where he states Laplace's determinism as irrelevant [11], and indeed, even the definition of the initial condition of a granular medium is ambiguous.

[1] Originally, Painlevé did not discussed the ill-posedness of NSCD. But Moreau himself [11] recognized the ill-posedness of the NSCD procedure is related to Painlevé's paradox.

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