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A contact smoothing method for arbitrary surface meshes using Nagata patches

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Highlights

- A new 3D contact surface smoothing approach for large deformation contact problems between deformable bodies is proposed.
- The local Nagata patch interpolation is used to smooth arbitrary surface meshes.
- The original curvature of the master surface is recovered using a relatively coarse mesh.
- The non-physical contact force oscillations usual in the faceted surface representation are eliminated.
- The accuracy, robustness and performance of the numerical simulations is improved adopting the surface smoothing method.

Abstract

This paper presents a contact surface smoothing method combined with the node-to-segment discretization technique to solve large deformation frictional contact problems between deformable bodies. The Nagata patch interpolation is used to smooth the surface mesh, providing a master surface with *quasi*-G^1 continuity between patches. Moreover, the local support of the interpolation method allows to deal with surface meshes of arbitrary topology (regular and irregular finite element discretizations), as well as hybrid meshes. The non-physical oscillations in the contact force evolution, induced by the faceted contact surface representation, are reduced using the proposed smoothing method. Furthermore, the smooth representation of the master surface allows a more accurately evaluation of the resulting stresses and forces, while providing an important improvement in convergence behaviour. Four representative numerical examples are used to demonstrate the advantages of the proposed contact smoothing method. The results show a significant improvement in the accuracy, robustness and performance of the numerical simulations using the smoothing approach, when compared with the piecewise faceted contact surface description.

Keywords: Finite element method; Frictional contact; Large sliding; Surface smoothing; Nagata patch; Augmented Lagrangian method

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1. Introduction

The description of the contact interaction across bodies plays an important role in many engineering problems. However, the numerical simulation of frictional contact between solids undergoing large deformations using implicit methods is still one of the most challenging tasks in computational mechanics, due to the highly nonlinear and non-smooth behaviour [1,2]. Indeed, the inequality constraints resulting from the impenetrability condition and the friction law are expressed by non-smooth multivalued relationships. The approaches usually considered for incorporating the contact constraints in the variational formulation of the equilibrium problem are: (i) the penalty method [3–6]; (ii) the Lagrange multiplier method [7–9] and (iii) the augmented Lagrangian method [10–12]. The penalty method is widely used due to its simple formulation, although the adequate choice of the penalty parameter may be difficult [13]. In fact, low values of the penalty parameter lead to the inaccurate enforcement of the contact constraint conditions (unacceptable penetration), while high values of the penalty parameters can lead to the ill-conditioning of the stiffness matrix. The Lagrange multiplier method exactly enforces the impenetrability and friction constraints, introducing extra variables (Lagrange multipliers), which represent the contact forces. The augmented Lagrangian method takes advantage of these two cited methods, allowing the exact representation of the contact constraints for a finite value of the penalty parameter. The generalized Newton method can be applied to solve the mixed system of equations (displacements and Lagrange multipliers as unknowns) [10,14], or alternatively the solution can be obtained with the Uzawa's algorithm [12], where the unknowns are only the displacements due to the nested update of dual variables (Lagrange multipliers).

The discretization of the contact interface in problems involving large sliding between deformable bodies is commonly performed with the node-to-segment (NTS) contact algorithm developed by Hallquist [4]. It is combined with the master–slave approach, where the enforcement of the contact constraints (impenetrability and friction conditions) is established in the nodes of the slave surface, preventing its penetration in the opposing discretized master surface. Since the geometry of the contacting surfaces is arbitrarily curved, its spatial discretization with low order finite elements introduces discontinuities in the surface normal vector field (facetization problem) [15]. Indeed, the bilinear surface facets defining the master surface are created using the exterior nodes of the low order solid elements defining the solid body. This geometric discontinuity leads to numerical instability, loss of the quadratic convergence rate in the non-linear solution scheme and non-physical oscillations in the contact force when a slave node slides over several master facets [16].

In order to overcome the chatter effect induced by the spatial discretization, several surface smoothing procedures have been proposed in the context of NTS formulation. Since the kinematic constraints are more accurately evaluated (the gap function and the surface normal vector), the robustness of the contact algorithms and the accuracy of the solution is significantly improved adopting a smoothing scheme [15,17–19]. In the NTS formulation only the master surface is smoothed, creating parametric patches over the discretized surface using the coordinates of the master nodes, dictating that the slave nodes interact with a smooth master surface. Different interpolation methods have been applied to smooth the contact surface mesh of deformable bodies: cubic Hermite interpolation [17], cubic Bézier [16,20], cubic Splines [21,22] and NURBS [23,24]. All these approaches were originally developed for 2D problems, thus its extension to describe contact surfaces in 3D is restricted to regular quadrilateral meshes, since the patches are obtained using the tensor product. In fact, the application of a smoothing method to arbitrary surface meshes is more difficult, because the number of neighbouring facets taken into account to generate the interpolated surface is arbitrary [25]. Only two approaches are available to deal with irregular 3D surface meshes. The first one, proposed by Puso and Laursen [26], uses Gregory patches in the surface smoothing, providing G^1 continuity between adjacent patches. It can be applicable to both regular and irregular meshes of quadrilateral facets. The other approach, developed by Krstulovic-Opara et al. [27], employs quartic Bézier patches in the interpolation using the nodes and the centroid of triangular finite elements. This approach leads to C^1 continuity everywhere except at the element nodes. On the other hand, the approach proposed by Belytschko et al. [28], is an alternative to the classic surface smoothing methods, performing the smoothing implicitly by constructing smooth signed distance functions from a scattered set of nodes, using a moving least-squares approximation. Although this method can be applicable to arbitrary surface meshes, the generated smoothed surface does not pass through the master nodes exactly, which can introduce some inaccuracies in the contact geometry [29]. Assuming that one contact body is rigid (Signorini problems), various computer aided design (CAD) interpolations can be used to define 3D smooth surfaces [30–32]. Nevertheless, this corresponds to a simpler problem than the case of two deformable bodies, since the master surface cannot be deformed.