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A shrunken edge algorithm for contact detection between convex polyhedral blocks

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ABSTRACT

The detection of contacts between interacting blocks is an important but time-consuming calculation in discontinuity-based numerical methods. This paper presents a new algorithm for the detection of contacts between arbitrary convex polyhedra with planar boundaries. In this algorithm, a pair of contacting blocks is identified as a main block and a target block. The concept of a shrunken edge is introduced in this paper. First, each vertex of the main block is shrunk toward the centre of the neighbouring faces. The shrinkage is infinitesimal yet useful for contact detection. Shrunken edges parallel to the original edges on the main block are established by connecting the shrunken points. Contact detection is then performed by determining the geometric relationship between a shrunken edge and its approaching face on the target block. From the three possible geometric relationships, all six contact types in three dimensions can be identified precisely, which allows for an easy and efficient detection process. Finally, the accuracy and effectiveness of the new contact algorithm are demonstrated through several examples in which two or more blocks collide in a three-dimensional domain.

1. Introduction

Geomaterials are typically discontinuous, containing joints and pre-existing cracks, and their failure is typically a combined continuum–discontinuum problem [1–3]. The properties and engineering behaviour of rock masses are typically governed by discontinuities. Thus, conventional numerical methods, which mainly use continuous models, are not suitable for such situations [4].

Methods of computational mechanics of discontinua include discrete element methods (DEM) [5–7], discontinuous deformation analysis (DDA) [8–11], the combined finite-discrete element method (FDEM) [12,13] and the numerical manifold method (NMM) [14,15]. The key to any discontinuity-based numerical method is a rigorous contact theory that can describe the interactions of multiple three-dimensional (3D) blocks [16]. Developing such a theory is a difficult task because contacts may exist between any combination of vertices, edges and faces, and contacts between blocks must be identified and updated continuously throughout the computation process [17]. Contact detection is still a major challenge in large-scale simulation despite advances in computer hardware and parallel techniques.

Contact detection is typically performed in two independent stages. The first stage, called a neighbour search, is a rough search that aims to optimally find the number of possible blocks in contact [18,19]. The most recent algorithms developed for neighbour searching include the no-binary-search algorithm [20], the spatial partitioning algorithm [21], the DESS algorithm [22] and the sweep-and-prune algorithm [23]. In the second stage, called geometric resolution, pairs of potentially contacting blocks obtained in the first stage are examined in detail to identify the contact type and calculate the contact forces. Cundall [5] introduced the well-known class of common plane (CP) methods. By translating and rotating the common plane, the contact type can be determined based on the number of vertices touching the common plane. This method has a complexity of order O(N) and has been successfully implemented in the 3D DEM code 3DEC [24]. Nezami et al. [25] showed that the number of iterations needed to find the correct CP for a contact between two blocks using conventional algorithms depended on the accuracy of the initial guess for the CP. They proposed the fast common plane (FCP) method to obtain the common plane, which was up to 40 times faster than the available search methods. Nezami et al. [26] proposed the shortest link method (SLM) to improve the efficiency in finding the accurate CP of a contact.

The Lin-Canny [27] closest features algorithm is a more sophisticated feature-based algorithm that computes the distance

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between disjoint polyhedra. The algorithm tracks and catches the closest features of a pair of convex polyhedral blocks. Mirtich [28] presented the V-Clip collision detection algorithm, which tracked the closest pair of features between convex polyhedra. Wu et al. [29] presented an algorithm that found vertex-to-face contacts as the first step toward a more comprehensive 3D analysis. Yeung et al. [30] and Jiang and Yeung [16] developed a point-to-face model, which formed part of a contact method to be used in 3D DDA. Wu [31] presented a new edge-to-edge contact calculation algorithm in which edge-to-edge contacts were transformed into vertex-to-face contacts. Yeung et al. [32] developed an edge-to-edge contact model that included methods for detecting the contact type and predicting the face where the first entrance would occur, as well as criteria for interpenetration. Contact transformation improved the efficiency of the calculation procedure. Keneti et al. [17] introduced a new algorithm for the detection of all contact types between convex blocks. After one of the approaching faces was identified as the main plane and the vertices within a certain distance were located, different algorithms were used to search for contact points and identify contact types in the global coordinate system. Beyabanaki et al. [33] presented a contact calculation algorithm for contacts between two polyhedra. In this algorithm, contact types were calculated from topological information about the two nearest points of the polyhedra. Boon et al. [34] introduced an algorithm for contact detection between convex polygonal and polyhedral particles in which a set of linear inequalities was used to define the space occupied by a polygon or polyhedron. Feng et al. [35] introduced a semi-spring and semi-edge contact model that could improve the efficiency of contact detection and simplify the steps for calculating contact forces.

The algorithm presented in this paper is intended to be a simple and useful tool for the resolution stage of contact detection. All six contact types can be identified precisely and efficiently by determining the geometric relationship between a shrunken edge and its approaching face. This new algorithm has been implemented in a computer program, and numerical results from several examples are provided to demonstrate the effectiveness of the algorithm.

2. Identification of the contact condition using shrunken edges

In contact search algorithms, the contact type is important because it determines the mechanical response of the contact. There are six types of contact for 3D blocks: vertex-to-vertex, vertex-to-edge, vertex-to-face, edge-to-edge, edge-to-face and face-to-face. The simplest approach is to test all possibilities, but this process is time consuming and unnecessary. In three dimensions, there are internal connecting links between the vertices, edges and faces. These links can be utilised to improve efficiency. In this section, we describe a shrunken edge model for computing the distance to an approaching face on a target block that can detect all six contact types between arbitrary convex polyhedra.

2.1. The concept of a shrunken edge

In hybrid continuous–discontinuous numerical methods, such as FDEM and NMM, blocks are initially neatly stacked, forming a continuous medium. Additionally, vertices and edges are shared by neighbouring faces. In this condition, it is difficult to identify contacts as vertex-to-vertex or edge-to-edge. In some cases, the contact condition cannot be determined correctly. As an example, Fig. 1a shows four blocks (A, B, C and D) with four vertices (a, b, c and d) located at the same position. In vertex-to-vertex contact detection, it is difficult to precisely identify contact between vertex a and vertices b, c and d (Fig. 1b). Similarly, contact detection will be difficult if more than two parallel edges are located together. These conditions are commonly found in hybrid continuous-discontinuous methods; however, few effective solutions have been proposed. To resolve this problem, the shrunken edge model is proposed for contact detection.

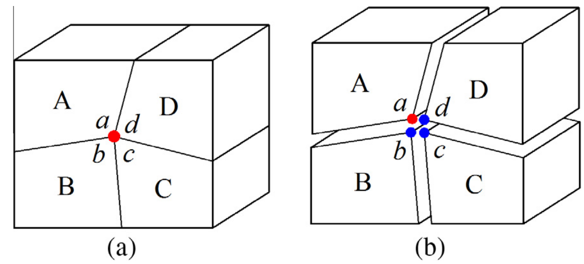

Fig. 1. (a) Vertices located at the same position. (b) Vertex-to-vertex contact is difficult to identify.

A shrunken edge, unlike a conventional edge, is located on a face. It is assumed that each vertex of a block shrinks toward the centre of the neighbouring faces. The shrunken distance is infinitesimal but still useful for contact detection. Then, a shrunken edge parallel to the initial edge is established by connecting the shrunken points. As an example, a hexahedral block is presented in Fig. 2a. $\mathbf{V}_1$ is one vertex of the block, and $\mathbf{P}_1$ is the shrunken point corresponding to $\mathbf{V}_1$ on face α. The position of point $\mathbf{P}_1$ will depend on the shrinkage distance, which can be expressed as

$$|\mathbf{P}_1\mathbf{V}_1| = \lambda|\mathbf{OV}_1| \tag{1}$$

where λ is the shrinkage coefficient, which can be 0.1–1.0% (1.0% is used in this paper). To find the correct contact, the search tolerance should be less than the shrinkage distance. All of the shrunken points in the block are obtained from the vertices in the same manner, and the shrunken edges are established. In Fig. 2b, points $\mathbf{P}_1$ and $\mathbf{P}_2$ are shrunken points and $\mathbf{E}_1$ is a shrunken edge.

Here, the shrunken edge is used only for the geometric resolution phase of contact detection, and the shrinkage coefficient λ can be regarded as a way to set the tolerance for contacts. The initial configuration of the block should be used when calculating the motion and deformation of a block. Therefore, there is no reduction in the block volume in this algorithm.

There are several benefits of the shrunken edge concept. First, it is easier to establish the initial contact conditions in a continuous block system using shrunken edges because the edges used for detection shrink into the neighbouring faces. Furthermore, the seamless transition of a geological body from a continuum to discrete description can be achieved using shrunken edges.

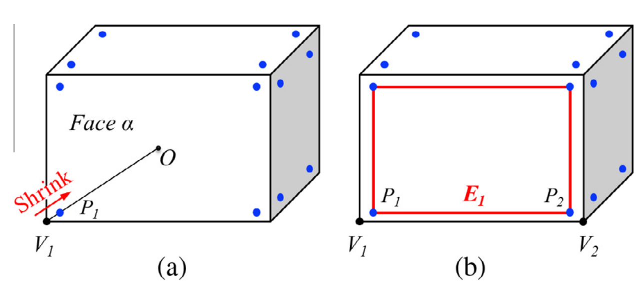

Fig. 2. (a) Shrunken points and (b) shrunken edges of a hexahedral block.