Computers and Geotechnics 87 (2017) 76–85

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A fast direct search algorithm for contact detection of convex polygonal or polyhedral particles

Fei Zheng [a,b,c], Yu-Yong Jiao [d,*], Michael Gardner [c], Nicholas Sitar [c]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Xiaohongshan, Wuchang District, Wuhan 430071, PR China
[b] University of Chinese Academy of Sciences, 19 A Yuquan Rd, Shijingshan District, Beijing 100049, PR China
[c] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720-1710, United States
[d] Faculty of Engineering, China University of Geosciences, Wuhan 430074, PR China

ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form 5 October 2016
Accepted 2 February 2017

Keywords:
Contact detection
Convex particles
Valid entrance
Initial detection
Updated detection

ABSTRACT

A fast direct search (FDS) algorithm is presented to increase the efficiency of contact detection for convex polygonal and polyhedral particles. All contact types are detected using only a small subset of these contact types: vertex-to-edge for polygons while vertex-to-face and edge-to-edge for polyhedra. First, an initial contact list is generated. Then in subsequent steps the contact list is updated by checking only local boundaries of the blocks and their separation. An exclusion algorithm is applied to avoid unnecessary examination for particles that are near but not-in-contact. The benchmark tests show that the FDS produces significant speed-up in various cases.

1. Introduction

Contact analysis is a necessary part of any computational method dealing with interaction between independent particles, such as in the discrete element method (DEM) and discontinuous deformation analysis (DDA). Contact detection comprises a significant portion of the computational effort in these types of analyses and therefore an accurate and efficient contact detection algorithm is essential. The aim of the contact detection phase is to provide possible contact types, contact points, contact normal directions and contact modes for all potential contact elements. Focusing on contacts between two particles, the particle shape becomes an important factor affecting computation accuracy and efficiency. In rock engineering, rock masses typically consist of densely packed polyhedral blocks and contact detection between polyhedral blocks is more complicated than between spheres, which are common in other applications. Moreover, the efficiency of contact detection between convex polyhedra is much higher than that for concave polyhedra, owing to the utilization of convex properties in the detection algorithm. This paper focuses on improving the efficiency and accuracy of contact detection for convex polyhedra.

From a geometrical perspective, convex polygons and convex polyhedrons have distinct properties which can be used in geometry representation and contact detection. For the geometric representation, two main methods are used. First, the point set of a two-dimensional (2-D) convex polygon or a three-dimensional (3-D) convex polyhedron can be algebraically represented by the intersection of several inequalities. The linear programming method [1] uses these expressions as a basis. Second, a boundary-representative method for polygons or polyhedra can be used. Boundaries of a polygon consist of vertices and edges while boundaries of a polyhedron consist of vertices, edges and faces.

Several convex polyhedron properties can be used in contact detection. First, a virtual infinite, rigid plane, named the common plane [2], can be found to separate two polygons or two polyhedra. This common plane can be considered as a reference plane to quickly compute the contact point and contact normal direction. Second, if a point is inside a polyhedron (polygon), this point must be inside all the half-spaces that form the polyhedron (polygon). As a result, if a point is outside any half-space forming the polyhedron (polygon), it is outside the polyhedron (polygon). This property is quite useful in being able to exclude vertices that are not in contact. Third, all 2-D planar angles, 3-D solid angles and dihedrals forming boundaries of convex polyhedrons are convex. Fourth, contacts of two convex polygons fall into the following types:

* Corresponding author.
E-mail address: yyjiao@cug.edu.cn (Y.-Y. Jiao).

http://dx.doi.org/10.1016/j.compgeo.2017.02.001
0266-352X/

vertex-to-vertex (v-v), vertex-to-edge (v-e) and parallel edge-to-edge (parallel e-e), whereas contacts of two convex polyhedra consist of: vertex-to-vertex (v-v), vertex-to-edge (v-e), vertex-to-face (v-f), crossing edge-to-edge (crossing e-e), parallel edge-to-edge (parallel e-e), edge-to-face (e-f) and face-to-face (f-f).

Numerous contact detection algorithms have been presented to improve the efficiency of detecting contacts between convex polyhedra. One approach is the common plane algorithm [2]. The common plane simplifies the contact detection process by testing the relationship of the common plane and each block instead of the relationship of two blocks. This approach was further optimized to produce the fast common plane (FCP) algorithm [3] and the shortest link method (SLM) [4]. Another genre is referred to as the direct search or improved direct search algorithms [8–10]. Other methods include the approaching face method [5], an improved approaching face algorithm [6], vertex-to-face searching algorithm [7] and multi-shell cover method [11]. Boon et al. [1] generalize contact between convex polyhedral particles as a convex optimization problem and used a linear program method to solve it.

Most recently, Shi [12] proved that contact between two convex polyhedra can be simplified to contact of a reference point and an entrance convex polyhedron. The boundary of the entrance polyhedron consists of contact covers (v-v, v-e, v-f and crossing e-e), and the position relationship of the reference point and contact covers determines the contact point, contact normal direction and contact mode. In this paper, we build on the theoretical work of Shi [12] and present the fast direct search (FDS) algorithm to improve the efficiency and accuracy of the contact detection. The FDS algorithm is applied in DDA to do discontinuous computation, two basic types (v-v and v-e) are used in 2-D case and four basic contact types (v-v, v-e, v-f and crossing e-e) are used in 3-D case for contact force computation.

2. The fast direct search algorithm (FDS)

The contact detection procedure consists of two search phases: neighbor search and delicate search. The neighbor search algorithm is based on the cell mapping method [2], but can be optimized using other neighbor search algorithms - such as NBS [13], DESS [14] or CGrid [15] - depending on the application. The fast direct search (FDS) algorithm is specifically concerned with the delicate search during which contact points, normals and modes are established.

FDS aims to obtain contact geometry information for convex polygonal or polyhedral particles more efficiently. In order to obtain higher efficiency, the FDS algorithm is executed in two phases. First, initial contact detection is executed and then updated contact detection is initiated when necessary. The initial contact detection phase forms a list of contact types for a new block geometry configuration, while the updated contact detection phase updates the contact information in this list starting from the contact detection results in the previous iteration.

Herein the basic concepts used in FDS are first introduced and then a detailed discussion of the contact detection process, data structures used and associated computational cost is presented.

2.1. Basic concepts used in contact detection

2.1.1. Valid entrance concept

Valid entrance is defined as a physical no-overlap status of potential contact pairs, similar to the concept of first entrance developed by Shi [12,16]. Valid entrance means that two potential contact objects should not have an overlapping area if their potential contact points are superimposed. In this way, a valid entrance check is used as a criterion in judging basic contact pairs. No overlap between two contact objects, from another perspective, is the same as the concept of a continuous face that separates these two objects. Here for convex objects, a plane separating the two objects can be found if they do not overlap.

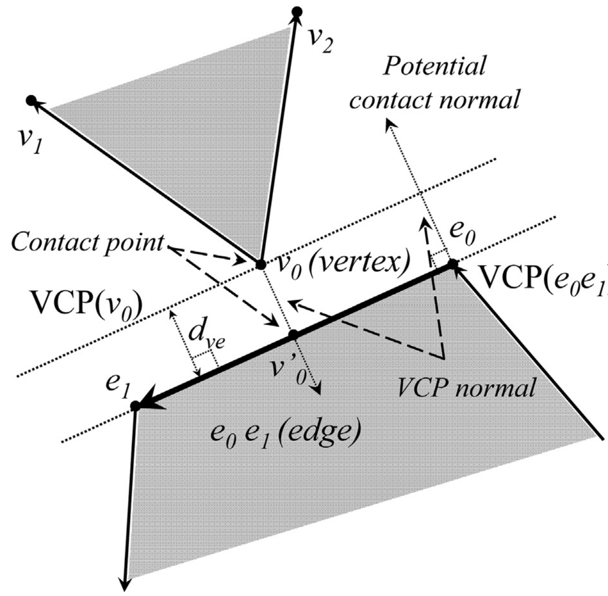

Fig. 1. Entrance of vertex-to-edge and its VCPs.

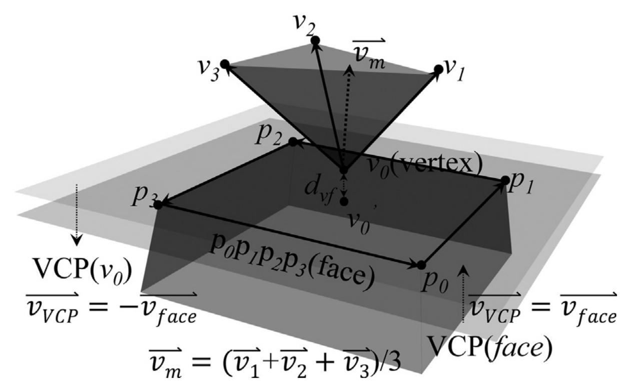

Fig. 2. Entrance of vertex-to-face and its VCPs.

A 2-D vertex-to-edge, v-e, entrance is valid if both edge vectors of the vertex angle point out of the half-space formed by the edge. As shown in Fig. 1, vertex v_0 and edge e_0e_1 is a valid entrance pair because both edge vector v_0v_1 and v_0v_2 point out of half-space surrounded by edge e_0e_1. In 2-D vertex-to-vertex, v(i)-v(j), entrance checking, all edge e(i) and e(j) joint to vertex v(i) and v(j) are considered. V(i)-v(j) entrance checking is subdivided into v(i)-e(j) and e(i)-v(j) entrance checking. If any v(i)-e(j) or e(i)-v(j) entrance is valid, v(i)-v(j) entrance is valid. Then half-space outer normals of all valid v(i)-e(j) or e(i)-v(j) entrances are stored in a list of potential contact normals.

In 3-D, vertex-to-face, v-f, or crossing edge-to-edge, e-e, entrance is valid if an infinite plane can be found that separates the vertex angle and the half-space surrounded by the face, or separates the two dihedrals connecting the two edges. For v-f entrance, the face can serve as the separating plane, and two steps are used in checking validity of v-f entrance. First, the average value of edge vectors that join the vertex angle is obtained and used to roughly judge if the vertex angle overlaps the half-space