Received January 16, 2020, accepted February 3, 2020, date of publication February 7, 2020, date of current version February 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2972317

Intersection Detection Algorithm Based on Hybrid Bounding Box for Geological Modeling With Faults

HONGJUAN WANG[1], XINGLI ZHANG[2], LONGQUAN ZHOU[1], XINMING LU[2], AND CHONG WANG[3,4]

[1]Department of Information Engineering, Shandong University of Science and Technology, Tai'an 271000, China
[2]College of Computer Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[3]Network and Information Center, Shandong University of Science and Technology, Qingdao 266590, China
[4]Beijing Key Laboratory on Integration and Analysis of Large-Scale Stream Data, Beijing 100144, China

Corresponding author: Hongjuan Wang (wanghongjuan@sdust.edu.cn)

This work was supported in part by the Science and Technology Development Plan Project of Tai'an City under Grant 2018GX0007, in part by the National Natural Science Foundation of China under Grant 51904173, in part by the University Science and Technology Plan Project of Shandong Province under Grant J18KA307, and in part by the Open Research Fund Program of Beijing Key Laboratory on Integration and Analysis of Large-Scale Stream Data under Grant KF2018004.

ABSTRACT In the process of 3D modeling of geological body with fault, it is the primary problem to calculate the intersecting line between fault plane and various geological models. To quickly locate geological models intersecting fault planes, this paper adopts the algorithm of intersection detection of hybrid bounding boxes. Firstly, the principal component analysis is used to generate the bounding box of the tightly bounding geological model. Then, based on the separation axis theorem, an improved algorithm is proposed to realize the intersection detection of hybrid bounding boxes, which effectively reduces the number of detection and improves the efficiency. Experimental results show that this algorithm can greatly shorten the time of intersection test, and improve the efficiency of intersection calculation. This paper provides an algorithm basis for quickly locating the geological model cut by fault plane.

INDEX TERMS Geological modeling, hybrid bounding box, oriented bounding box (OBB), principal component analysis (PCA), separation axis theorem (SAT).

I. INTRODUCTION

Bounding box technology is widely used in industrial design, numerical control machining, computer graphics, virtual simulation and other fields, and can solve many practical problems. In collision detection, the efficiency of intersection testing can be improved significantly by replacing complex geometric objects with the minimum bounding box of real objects [1], [2]. Domestic and foreign scholars have studied the solution method of a single bounding box [3]–[8]. Due to the large number of models and different shapes in the complex environment, an algorithm of single bounding boxes cannot meet the environmental requirements. Therefore, many scholars have studied the algorithm of hybrid bounding box. Literature [9], [10] focused on the algorithm of hybrid bounding box of Axis Aligned Bounding Box (AABB) and Oriented Bounding Box (OBB). In literature [11], collision detection algorithm was optimized by dividing object shape by deflecting ball rate. Literature [12], [13] studied the algorithm of hybrid bounding box in big data environment and complex environment. Literature [14] proposed a cloud-based hybrid collision detection based on basic geometric elements, which is suitable for large-scale and complex collision detection algorithms. In literature [15], a hybrid collision detection algorithm based on bounding box tightness and multi-layer modeling structure was studied.

In this paper, the bounding box technique is applied to the intersection detection of geological modeling. For the modeling of complex geological bodies, we adopt the method of fault plane cutting geological model. It is the primary problem to calculate intersection line between fault plane and each geological body quickly. There are different geological models such as lens and collapse columns in underground space, it is difficult to improve the speed of intersection detection by using a single bounding box technology. In order to adapt to geological models of different shapes and obtain the bounding box that closely surrounds the geological models, the algorithm of intersection detection of hybrid bounding

The associate editor coordinating the review of this manuscript and approving it for publication was Shouguang Wang.

box is proposed. According to the shape of the geological body, the compact box is chosen to replace the complex geological model, so as to eliminate the disjoint objects more accurately.

The rest of this paper is organized as follows. Section 2 presents the method of creating various bounding boxes in detail. Section 3 presents the related theory and algorithm of intersecting detection of bounding boxes. In Sect. 4, experimental results are shown to verify the effectiveness of the proposed method. Finally, the conclusions are summarized in Sect. 5.

II. CREATE A BOUNDING BOX OF GEOLOGICAL MODEL

Principal component analysis (PCA) is used to create the bounding box. According to the structural characteristics and spatial geometric parameters of the geological model, this paper establishes the axis-aligned bounding box (AABB), oriented bounding box (OBB), and spherical bounding box (SBB) of each geological model, calculates their volume, and selects the bounding box with the smallest volume as the bounding box of the geological model. This method can increase the fit of the bounding box of different objects, and reduce the test times between basic geometric elements. The process of creating the bounding box of geological model is shown in Fig. 1.

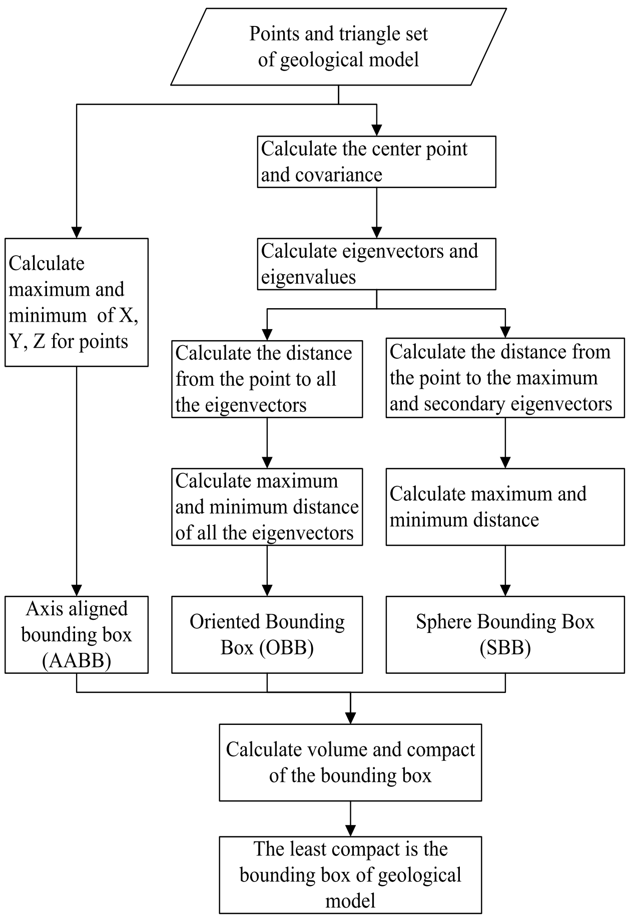


FIGURE 1. Flow chart of creating bounding box of geological model.

A. ALGORITHM OF GENERATING AXIS ALIGNED BOUNDING BOX (AABB)

AABB is a cuboid whose direction is consistent with the x, y and z axis of the world coordinate system. AABB adopts the expression method of center - direction axis - half length. The steps are as follows:

1) The three axis vectors of the coordinate system are called $a_x = (1, 0, 0)$, $a_y = (0, 1, 0)$, $a_x = (0, 0, 1)$. The maximum and minimum values of the point set on the three axis vectors such as x_{max}, x_{min}, y_{max}, y_{min}, z_{max} and z_{min} are calculated by divide-and-conquer algorithm.

In algorithm 1, MaxV is the maximum of elements. MinV is the minimum of elements. The algorithm is described as follows:

Algorithm 1 Search for the Maximum and Minimum Values of Elements

Input: a [1, n].
1: if n=1, then MaxV = a[1], minV= a[1].
2: if n=2, then MaxV = Max{a[1], a[n]}, MinV= Min {a[1], a[n]}.
3: if n>2, then divide a [1, n] into left and right intervals a [1, mid] and a [mid+1, n] according to mid=(1+n)/2. Recursively solve the maximum and minimum element of left interval called lmax and lmin, and the maximum and minimum element of right interval called rmax and rmin.
4: MaxV = Max (lmax, rmax), MinV= Min (lmin, rmin).
Output: MaxV, MinV.

In algorithm1, steps are used to obtain the maximum and minimum values, and the recurrence of comparison times is shown in (1).

$$\begin{cases} T(1) = T(2) = 1 \\ T(n) = 2T\left(\frac{n}{2}\right) + 1 \end{cases} \tag{1}$$

It can be deduced that T (n) is equal to O (n), that is, the time complexity of algorithm is O (n).

1) Calculate the coordinate of center point, shown in (2).

$$\begin{cases} C_x = \frac{1}{2}(x_{max} - x_{min}) \\ C_y = \frac{1}{2}(y_{max} - y_{min}) \\ C_z = \frac{1}{2}(z_{max} - z_{min}) \end{cases} \tag{2}$$

2) Calculate the side length of AABB, shown in (3).

$$\begin{cases} l_x = x_{max} - x_{min} \\ l_y = y_{max} - y_{min} \\ l_z = z_{max} - z_{min} \end{cases} \tag{3}$$

3) Calculate the volume of AABB, shown in (4).

$$V_{AABB} = l_x \times l_y \times l_z \tag{4}$$

AABB is used for the elongated geological model with the same direction as the axis. The normal vector of AABB is parallel to the fixed coordinate system. The characteristic of AABB is to take advantage of the fixed axis to reduce the dimension of the three-dimensional intersection problem to three single axis. The coordinate maximum value of the two bounding boxes on each axis is compared. Although AABB has a simple structure and can realize intersection detection quickly, it has poor bounding effect, especially for objects with given coordinate system inclined axis direction, which will lead to poor detection accuracy.

B. ALGORITHM OF GENERATING ORIENTED BOUNDING BOX (OBB)

Oriented Bounding Box (OBB) is a cuboid in any directions, which is widely used in hierarchical bounding boxes. There are two ways to create OBB. One is to obtain the OBB by three-dimensional transformation of AABB; the other is to determine a direction bounding box by covariance matrix. The key to creating OBB is to find an optimal geometric direction, and determine the minimum size of bounding boxes in this direction. No matter which method is adopted, it is a difficult problem to design an efficient algorithm to create a compact OBB.

In this paper, the principal component analysis (PCA) method is adopted to create the OBB in the same coordinate system. The representation of center-orientation-length is adopted, four variables are defined, and each data type is a three-dimensional vector. In order to reduce memory consumption, only two directional axes are stored, and the cross product is used to calculate the third axis during detection. The steps are as follows:

1) CALCULATE THE CENTER OF OBB

The geological model is composed of n triangles, and the vertexes of the ith triangle are called P_i (P_i.x, P_i.y, P_i.z), Q_i (Q_i.x, Q_i.y, Q_i.z) and R_i (R_i.x, R_i.y, R_i.z), the coordinate of center point is called (C_x, C_y, C_z), as shown in (5).

$$\begin{cases} C_x = \dfrac{1}{3n}\sum_{i=1}^{n}(P_i.x + Q_i.x + R_i.x) \\ C_y = \dfrac{1}{3n}\sum_{i=1}^{n}(P_i.y + Q_i.y + R_i.y) \\ C_z = \dfrac{1}{3n}\sum_{i=1}^{n}(P_i.z + Q_i.z + R_i.z) \end{cases} \tag{5}$$

2) CALCULATE THE DIRECTION AXIS OF OBB

The covariance matrix C is calculated according to triangle vertex coordinates.

$$\begin{cases} C_{11} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{ix}}\cdot\overline{P_{ix}} + \overline{Q_{ix}}\cdot\overline{Q_{ix}} + \overline{R_{ix}}\cdot\overline{R_{ix}}) \\ C_{12} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{ix}}\cdot\overline{P_{iy}} + \overline{Q_{ix}}\cdot\overline{Q_{iy}} + \overline{R_{ix}}\cdot\overline{R_{iy}}) \\ C_{13} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{ix}}\cdot\overline{P_{iz}} + \overline{Q_{ix}}\cdot\overline{Q_{iz}} + \overline{R_{ix}}\cdot\overline{R_{iz}}) \\ C_{22} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{iy}}\cdot\overline{P_{iy}} + \overline{Q_{iy}}\cdot\overline{Q_{iy}} + \overline{R_{iy}}\cdot\overline{R_{iy}}) \\ C_{23} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{iy}}\cdot\overline{P_{iz}} + \overline{Q_{iy}}\cdot\overline{Q_{iz}} + \overline{R_{iy}}\cdot\overline{R_{iz}}) \\ C_{33} = \dfrac{1}{3n}\sum_{i=1}^{n}(\overline{P_{iz}}\cdot\overline{P_{iz}} + \overline{Q_{iz}}\cdot\overline{Q_{iz}} + \overline{R_{iz}}\cdot\overline{R_{iz}}) \end{cases} \tag{6}$$

In (6), $\overline{P_{ix}} = P_i.x - C_x$, $\overline{P_{iy}} = P_i.y - C_y$, $\overline{P_{iz}} = P_i.z - C_z$, $\overline{Q_{ix}} = Q_i.x - C_x$, $\overline{Q_{iy}} = Q_i.y - C_y$, $\overline{Q_{iz}} = Q_i.z - C_z$, $\overline{R_{ix}} = R_i.x - C_x$, $\overline{R_{iy}} = R_i.y - C_y$, $\overline{R_{iz}} = R_i.z - C_z$.

The covariance matrix C is a symmetric matrix. All eigenvalues and eigenvectors of a real symmetric matrix are obtained by using Jacobi algorithm. The three eigenvectors are orthogonal and perpendicular in pairs, and the OBB axes are called b_u, b_v and b_w.

3) CALCULATE THE DISTANCE OF THE POINT VECTOR AND GET THE MAXIMUM AND MINIMUM VALUES

The distances from points to three projective surfaces are called d_u, d_v and d_w, as shown in (7).

$$\begin{cases} d_u = b_u.\overline{CP_i} \\ d_v = b_v.\overline{CP_i} \\ d_w = b_w.\overline{CP_i} \end{cases} \tag{7}$$

where $\overline{CP_i}$ is vector of from the center point to P_i. If the point is on the upper side of the projection plane, the distance is positive; otherwise, the distance is negative. Algorithm 1 is used to calculate the maximum and minimum values of vector distances.

4) CALCULATE THE SIDE LENGTH AND VOLUME OF OBB

According to the maximum and minimum values of the distance on each axis, side lengths are calculated, as shown in (2), and the volume of OBB is calculated according to the side lengths, as shown in (3).

The creation process of OBB is described in detail above. For the geological model with slender shape and direction deviating from the coordinate axis, OBB is adopted to establish the OBB with minimum volume.

C. ALGORITHM OF GENERATING SPHERE BOUNDING BOX (SBB)

The sphere bounding box (SBB) is a kind of bounding body with good simplicity and flexible structure. It adopts the expression of center-radius. The radius of the sphere can be obtained by calculating the distance between the furthest vertex and the sphere center, i.e. passing through the longest axis of the object. The calculation of SBB is similar to that of OBB. The method of calculating the center point coordinates, direction axis and side length of SBB is the same as that of OBB. The steps are as follows:

1) Calculate the coordinate of center point of SBB.
2) Calculate the direction axis of SBB.
3) Calculate the distance of the point vector and get the maximum value.
4) Calculate the side lengths l_x, l_y and l_z of SBB, as shown in (8). Let's say $l_x > l_y > l_z$.

$$r = \sqrt{l_x^2 + l_y^2} \tag{8}$$

where r is radius of SBB.

5) Calculate the volume of SBB, as shown in (9).

$$V_{SBB} = \frac{4}{3}\pi r^3 \tag{9}$$

SBB is used as the uniform geological model with a shape close to a sphere and distributed on each coordinate axis. It is very simple to test the intersection of two sphere bounding boxes. It is only necessary to calculate the distance between the centers of the two SBB that is greater than the sum of the radii of the two spheres, and then it can be judged that they do not intersect. For a geological body of nearly spherical shape, the algorithm efficiency of SBB is relatively high. But for geological models with very uneven spatial structure distribution, SBB is low tightness and there is a large space surplus. It is easy to cause great spatial redundancy, and lead to the increase of preliminary detection time.

D. THE COMPACTNESS OF BOUNDING BOX

The compactness of bounding box is defined as the volume of the geological model divided by the volume of bounding box. For the same geological body, the compactness of bounding box is the highest with the smallest volume. In reality, the geological body is irregular, and there is a large gap between the generated bounding box and the geological model. If the compactness is too low, the final detection result will be affected. Therefore, we choose the bounding box with the smallest volume as the bounding box of the geological model for intersection detection.

In Fig. 2, the AABB and OBB of the geological model are created, and their volumes are calculate respectively. The volume of OBB is the smallest, and OBB is the bounding box that closely surrounds the geological model.

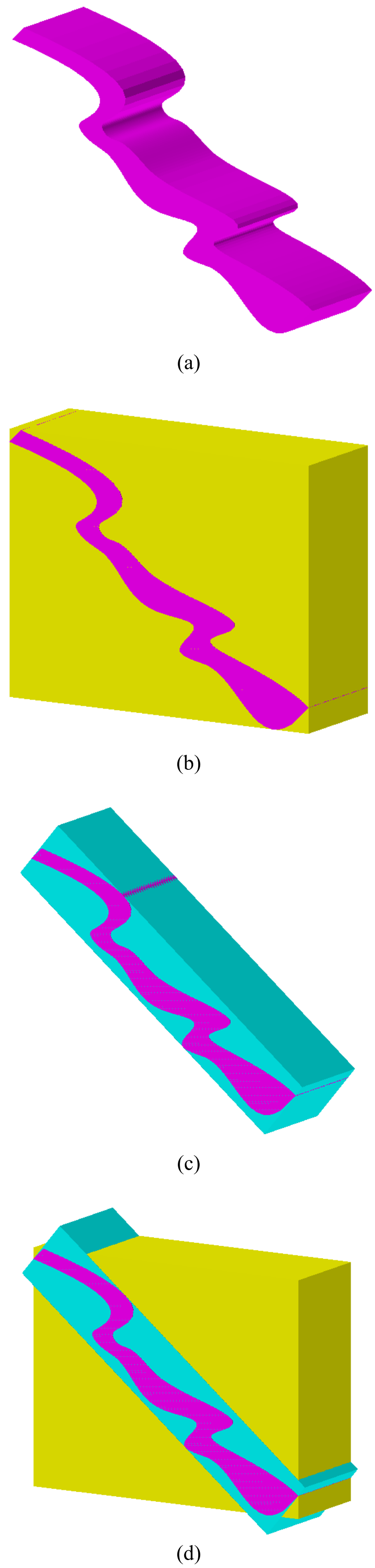


FIGURE 2. Bounding box of geological model (a) this is geological model. (b) This is AABB. (c) This is OBB. (d) This is AABB and OBB of geological model.

III. THE THEOREM AND ALGORITHM OF INTERSECTING DETECTION OF BOUNDING BOXES

Based on the separation axis theorem, an improved algorithm is proposed for intersection detection of bounding boxes.

A. SEPARATION AXIS THEOREM

The separation axis theorem (SAT) is an algorithm for detecting intersection of convex polygons or convex polyhedron,

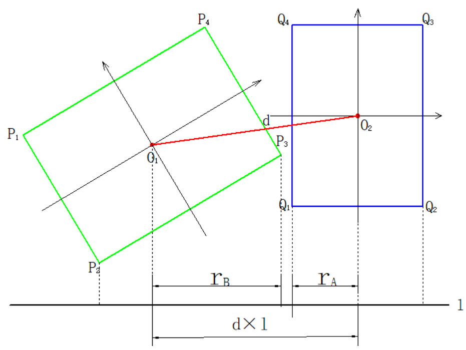


FIGURE 3. Separation axis theorem of OBB and AABB.

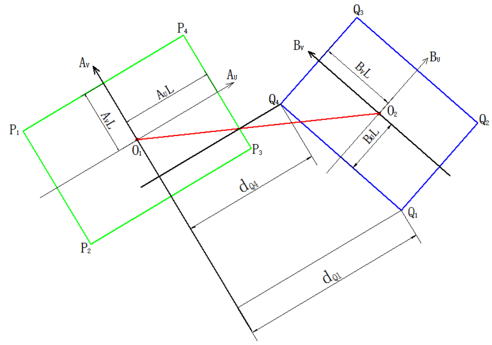


FIGURE 4. The judgment of bounding boxes separation.

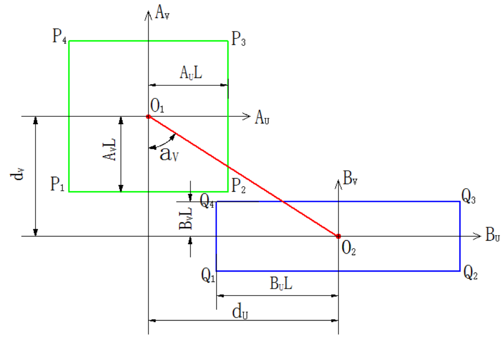


FIGURE 5. The parallel direction axes.

which is widely used in collision detection. The principle of SAT is that if a separation axis can be found so that the projection of two objects on the axis does not overlap, then the two objects do not intersect. The researches of intersection detection of bounding boxes are based on the separation axis theorem [16], [17]. In 2D, the separation axis is the vertical vector of each edge of bounding box A and bounding box B. Only by enumerating these vertical vectors, the intersection or separation of two bounding boxes is judged. If the number of edges of bounding box A and bounding box B are m and n respectively, the number of potential separation axis is m + n. The vertical vector of vector (X, Y) is (Y, −X) or (−Y, X), projection of each vertex is calculated respectively on the vertical vector. If projection area does not overlap, they do not intersect. If there is overlap, they may intersect, need to continue testing until each edge, if no gaps are found after each edge is examined, bounding box A and B is the intersection.

As shown in Fig. 3, the overlapping areas of the separation axis are judged and their position relations are finally determined.

In 3D, OBB is a cuboid, each OBB has 3 surface directions and 3 edges, and the number of potential separation axes between the two OBBs is 15 in total. For each potential separation axis, the interval detection method is used to calculate the coordinate values of the eight vertices of the bounding box, and the projection of each vertex on the separation axis is compared.

The principle of the SAT is simple and easy to understand. The key to implementing this algorithm is how to find the separation axis. Due to the large computation amount of the separation axis algorithm, it is difficult to realize the separation axis test in practical application, so it is necessary to optimize the collision detection algorithm of the separation axis.

In order to reduce the number of intersection detection and improve the efficiency of intersection detection, in this paper, based on the theory of separation axis, an improved algorithm is proposed. The intersection and separation of two bounding boxes are judged by comparing the distance from the point to the direction axis with the corresponding half length, as shown in Fig. 4.

According to (10), we judge that the two bounding boxes are separated.

$$\begin{cases} d_{Q4} \geq A_u L \\ d_{Q1} \geq A_u L \end{cases} \tag{10}$$

Considering the relationship between the direction axes of the two bounding boxes, we propose an improved algorithm for bounding box intersection detection. The algorithm framework is described in detail by taking the two-dimensional bounding box as an example. The corresponding proof process for using the priority of separation axis is as follows:

Case 1: The direction axes of the two bounding boxes are parallel, we directly use the method of distance comparison to judge whether the two bounding boxes intersect. In Fig. 5, O_1 and O_2 is the center point of bounding box A and B. A_u and A_v is the direction axes of bounding box A. B_u and B_v is the direction axes of bounding box B. a_v is the angle between the direction axes of bounding box A and the center line.

As long as (11) or (12) is true, we can determine that the two bounding boxes do not intersect.

$$|O_1O_2| \sin a_v \geq (A_u L + B_u L) \tag{11}$$

$$|O_1O_2| \cos a_v \geq (A_v L + B_v L) \tag{12}$$

Case 2: The direction axes of the two bounding boxes are unparalleled. The position relationship between bounding box A and bounding box B and their circumscribed circles are shown in Fig. 6.

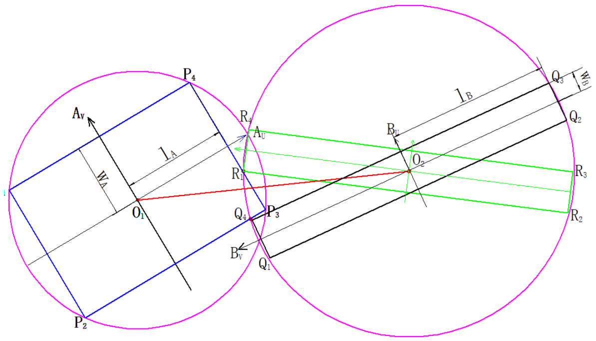


FIGURE 6. The unparalleled direction axes.

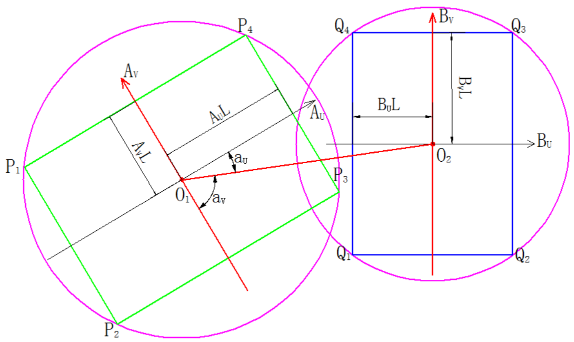


FIGURE 7. Example of intersection detection of OBB and AABB.

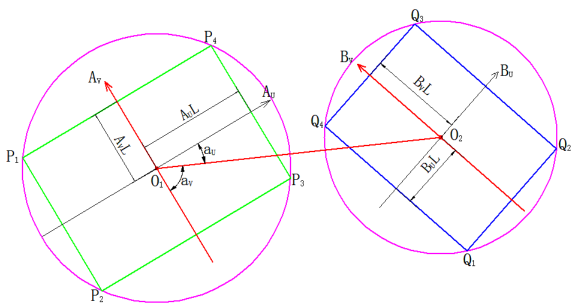


FIGURE 8. Example of intersection detection of OBB and OBB.

If the length of the centerline is greater than the sum of the two radii, then the two bounding boxes are separated. As shown in (13), l_A and w_A is the length of the sides of the bounding box A, l_B and w_B is the length of the sides of the bounding box B.

$$|O_1O_2| \geq \sqrt{l_A^2 + w_A^2} + \sqrt{l_B^2 + w_B^2} \tag{13}$$

Otherwise, the priority of the separation axis is determined by calculating the angle between center point vector and direction axis of bounding box.

B. ALGORITHM OF INTERSECTING DETECTION BETWEEN OBB AND AABB OR OBB

Intersection detection between OBB and AABB or OBB is shown in Fig. 7 and Fig 8. O_1 and O_2 are center points of bounding boxes.

In algorithm 2, bounding box A is OBB, and bounding box B is AABB or OBB. Flag=0 indicates that the bounding boxes do not intersect. Flag =1 indicates that the bounding boxes intersect. The algorithm is described as follows:

Algorithm 2 Intersection Detection of OBB and AABB or OBB

Input: Bounding box A, Bounding box B
  Determine the relationship between A_u and B_u.
  If the direction axis A_u and B_u are parallel then
    If (11) or (12) is true then
      Flag=0
    Else
      Flag=1
    End if
  else
    If (13) is true then
      Flag=0
    Else
      Calculate the center vector O_1 O_2.
      If the center vector O_1O_2 is (0,0,0) then
        flag=1
      else
        Calculate the angle a_u and a_v.
        If $a_u \geq a_v$ then
          Calculate the distance d_i from each vertex of bounding box B to A_u.
          If every $d_i > A_vL$ then
            flag=0
          else
            Calculate the angle b_u and b_v.
            If $b_u \geq b_v$ then
              Calculate the distance d_i from each vertex of bounding box B to A_u.
              If every $d_j > B_vL$ then
                flag=0
              else
                flag=1
Output: flag=0 or flag=1

C. ALGORITHM OF INTERSECTING DETECTION BETWEEN OBB AND SBB

Intersection detection of OBB and SBB is shown in Fig. 9. O_1 is center point of OBB, and O_2 is center points of SBB.

In algorithm 3, bounding box A is OBB, and bounding box B is SBB. Flag =0 indicates that the bounding boxes do not intersect. Flag =1 indicates that the bounding boxes intersect. The algorithm is described as follows:

Although the intersection detection between the bounding boxes can exclude a large number of disjoint triangles between the models, the triangles still need to be tested in many cases. In recent years, domestic and foreign researches on triangles intersection detection have been very active [18]–[21], algorithm of intersecting detection between triangle and triangle has been described in detail in literature [22].

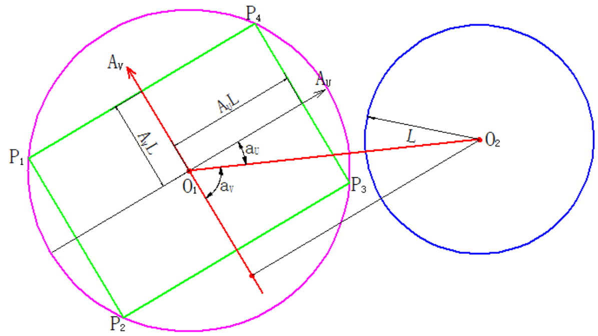


FIGURE 9. Example of intersection detection of OBB and SBB.

Algorithm 3 Intersection Detection of OBB and SBB

Input: Bounding box A, Bounding box B
  Determine the position relationship between circumscribed circle of bounding box A and bounding box B
If the distance between the centers of the two circles is greater than the sum of the radii of the two circles
    Flag=0
  Else
    Calculate the center vector O_1O_2.
    If the center vector O_1O_2 is (0,0,0) then
      flag=1
    else
     Calculate the angle a_u and a_v.
      If $a_u \geq a_v$ then
        Calculate the distance d from the center point O_2 to the direction axis A_u.
        If $d > A_V L + R$ then
          flag=0
        End if
      else
        Calculate the distance d from the center point O_1 to the direction axis A_v.
        If $d > A_u L + R$ then
          flag=0
        else
          Calculate the distance di from vertexes to the O_2.
          The minimum value of d_i is L.
          If $L > R$ then
            flag=0
          else
            flag=1
Output: flag=0 or flag=1

IV. ALGORITHM TESTING AND ANALYSIS

According to the method of this paper, firstly, the bounding box of the geological model is established. In Fig. 10, the geological model consists of 2084 triangles with a volume of 121347584.877803. The fault plane consists of 14 triangles. In order to quickly determine the triangle intersecting the fault plane, the bounding box AABB and OBB of the geological model are calculated. The AABB volume is 885258519.759109, the OBB volume is 300655336.309702. Their compactness is 0.1371 and 0.4036 respectively. Therefore, the bounding box of the geological model is OBB. The intersection points of these triangles and the fault plane triangles are calculated to get the intersecting lines, shown in Fig. 10(c).

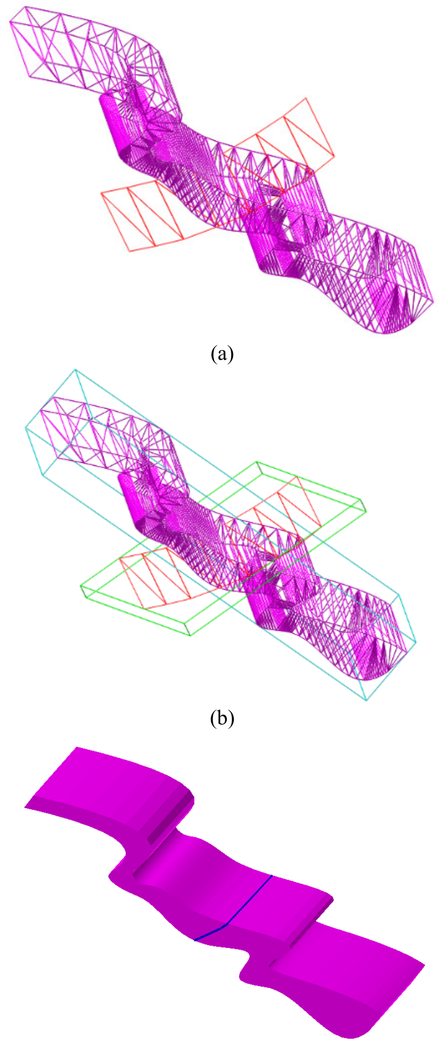


FIGURE 10. Example of intersection detection: (a) this is geological model and fault. (b) This is geological model OBB and fault OBB. (c) This is intersecting line of geological model.

The next step is the intersection detection of the bounding box. OBB can more closely surrounded model, but due to the arbitrariness of the orientation, the intersection detection between OBB and OBB or AABB becomes more complex. Traditional detection methods need to test the most 15 separation axis, including the intersection detection of 6 separating axes in the axial direction of the two bounding boxes and the intersection detection of 9 separating axes in the axial cross product. In all the tests, if there is a separation axis, it can be

TABLE 1. Comparison of calculation amount of algorithm.

algorithm	addition and subtract	multiply-divide	absolute value	comparison	total count
literature [20]	42	56	0	28	126
literature [21]	5	28	0	38	71
this paper	27	24	0	12	63

determined that the two OBBs do not intersect. Single detection operation includes 60 times of addition and subtraction, 81 times multiplication and division, 24 times absolute value and 15 times comparison [23]. Literature [24] proposed an algorithm of hybrid layer bounding box using 5 separating axes to detect bounding boxes. The algorithm of intersection detection is very complex, and how to quickly detect OBB intersection is the focus of research. After collision detection of OBB and OBB, it is determined the number of triangles intersecting with the fault plane.

In the stage of intersection detection, the total calculation amount of algorithm can be regarded as the sum of addition, subtraction, multiplication, division and comparison operation. By comparison with the classic algorithms of Tropp as well as the algorithm proposed in literature [21], the comparison of calculation amount of each algorithm is shown in table 1. The method of this paper can reduce the number of intersecting detection and improve the detection efficiency.

V. CONCLUSION

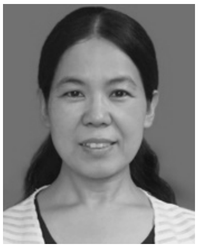
In the process of modeling and cutting analysis of complex geological body with faults, it is necessary to locate the intersecting areas quickly and accurately. Aiming at the low efficiency of intersection detection caused by the large number of models in complex geological conditions, the bounding box technology is used. According to the shape of the geological model, the bounding box of high-density is select to replace the complex geological model for intersection detection, so as to remove the disjoint objects more accurately and reduce the times of intersection testing.

Algorithm includes two stages. The first stage is to create the bounding box. The principal component analysis (PCA) is used to calculate the mean and covariance matrix, and the Jacobi algorithm is used to calculate all the eigenvalues and eigenvectors of the real symmetric matrix. The maximum and minimum values of the distance are obtained by divide-and-conquer strategy. The second stage is intersect detection of hybrid bounding boxes. Based on the theory of separation axis, an improved algorithm is proposed to judge the intersection and separation of two bounding boxes more quickly.

The experimental results show that the algorithm based on the compactness of the bounding box of the geological model can greatly shorten the time of intersecting test, and improve the speed of detection on the premise of ensuring the accuracy of detection. This study provides an algorithm basis for quickly locating the geological model that intersects the fault.

REFERENCES

[1] Y. Xun-Gang, S. Dian-Zhu, L. Yan-Rui, and X. Zhao, "Fast solution method of quasi minimum bounding box for 3D shape," *Modular Mach. Tool Autom. Manuf. Techn.*, no. 7, pp. 51–54, 2017.
[2] L. Tao, W. Zeng-Bo, and L. Zhan-Li, "Bounding box technology and its application during collision detection process," *J. Xi'an Univ. Sci. Technol.*, vol. 26, no. 3, pp. 395–399, 2006.
[3] C. Bai-Song, Y. Xue-Mei, and A. Li, "Minimum bounding box calculation based on nonlinear principle component analysis," *Comput. Integr. Manuf. Syst.*, vol. 16, no. 11, pp. 2375–2378, 2010.
[4] H. Huai-Qing, Y. Jun-Hong, and Y. Guo-Qing, "Study of OBB hierachical structure and its application speed-up algorithm," *Comput. Eng.*, vol. 31, pp. 234–235, 2005.
[5] S. Xu-Sheng, Q. Li-Hong, and Z. Zuo-Wei, "Algorithm of collision detection based on improved oriented bounding box," *J. Hunan Univ. (Natural Sci.)*, vol. 41, no. 5, pp. 26–31, 2014.
[6] S. Cheng and Y. Feng, "Fast collision detection algorithm of cylinders based on generatrices," *J. Jilin Univ. (Sci. Ed.)*, vol. 53, no. 2, pp. 291–296, Feb. 2015.
[7] Z. Xing-Xing, X. Ming-Hong, and Z. Ya-Yun, "Fast collision detection algorithm based on uniform spatial subdivision and linear programming," *Comput. Eng. Appl.*, vol. 53, no. 23, pp. 236–240, 2017.
[8] Z. Er-Xi, X. Min, and H. Yuan-Jun, "A collision detection algorithm using delaunay triangulation," *J. Graph.*, vol. 36, no. 4, pp. 516–520, 2015.
[9] L. Xiaobin, "Research and implementation of collision detection algorithms based on hybrid bounding box," M.S. thesis, College Comput. Sci. Eng., South China Univ. Technol., Guangzhou, China, 2015.
[10] W. Chao, Z. Zhili, L. Yong, and W. Shaodi, "Improved hybrid bounding box collision detection algorithm," *J. Syst. Simul.*, vol. 30, no. 11, pp. 4236–4243, 2018.
[11] S. Jing-Guang, W. Su-Hong, and Z. Ji-Lin, "Optimisation algorithm for bounding box collision detection based on shape classification," *Comput. Appl. Softw.*, no. 2, pp. 242–245, 2016.
[12] L. Jian, W. Ming-Yue, Y. Ru-Jing, C. Chun-Ling, and H. Ya-Ting, "Optimization of collision detection algorithm based on hybrid hierarchical bounding box under background of big data," *J. Jilin Univ. (Sci. Ed.)*, vol. 55, no. 3, pp. 673–678, 2017.
[13] X. Wei-Chao, "Research on the hybrid bounding box collision detection algorithm in complex environment," M.S. thesis, College Inf. Eng., Jiangxi Univ. Sci. Technol., Jiangxi, China, 2018.
[14] A. Xiaoguang and L. Ling, "A study of collision detection algorithm based on cloud computing model," in *Proc. Int. Conf. Intell. Transp., Big Data Smart City (ICITBS)*, Dec. 2016, pp. 55–58.
[15] H. Chunan, X. Weichao, and W. Zhendong, "Hybrid collision detection a lgorithm relying on the tightness ratio of bounding volume and multilayer modeling structur," *Sci. Technol. Eng.*, vol. 18, no. 16, pp. 74–80, 2018.
[16] Y. Z. Zhang, C. Fan, and X. F. Luo, "Separating-axis calculation of motion path for continuous collision detection of convex polyhedrons," *J. Comput.-Aided Des. Comput. Graph.*, vol. 25, no. 1, pp. 7–14, 2013.
[17] L. Chao, J. Xia-Jun, and S. Hui-Bin, "Improved collision detection algorithm based on oriented bounding box," *Comput. Technol. Develop.*, vol. 28, no. 6, pp. 43–48, 2018.
[18] X. Qiang, L. Xiao-Feng, and M. Deng-Wu, "A survey of triangle and triangle intersection test," *Comput. Simul.*, vol. 23, no. 8, pp. 76–78, 2006.
[19] T. Möller, "A fast triangle-triangle intersection test," *J. Graph. Tools*, vol. 2, no. 2, pp. 25–30, Jan. 1997.
[20] O. Tropp, A. Tal, and I. Shimshoni, "A fast triangle to triangle intersection test for collision detection," *Comput. Animation Virtual Worlds*, vol. 17, no. 5, pp. 527–535, Dec. 2006.
[21] G. Li-Wen, D. Yu-Xi, and W. Li-Ping, "Intersection test algorithm for spacial triangular facets," *J. Tsinghua Univ. (Sci. Technol.)*, vol. 57, no. 9, pp. 970–974, 2017.
[22] W. Hong-Juan, K. Shu-Ting, Z. Xing-Li, L. Xin-Ming, and Z. Long-Quan, "Robust Boolean operations algorithm on regularized triangular mesh and implementation," *Multimedia Tools Appl.*, 2018.
[23] S. Xiao-Guang and W. Ming-Qiang, "Research on collision detection algorithm based on bounding box," *Mod. Manuf. Eng.*, no. 4, pp. 87–91, 2009.
[24] J. W. Chang, W. P. Wang, and M. S. Kim, "Efficient collision detection using a dual OBB-sphere bounding volume hierarchy," *Comput.-Aided Des.*, vol. 42, no. 1, pp. 50–57, 2010.

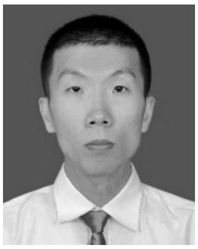


HONGJUAN WANG was born in Dongying, Shandong, China, in 1974. She received the M.S. degree in computer systems architecture and the Ph.D. degree in computer software and theory from the Shandong University of Science and Technology, in 2007 and 2013, respectively.

She is currently an Associate Professor with the Department of Information Engineering, Shandong University of Science and Technology. Her main research interests are computer graphics, computer aided design, key technology of 3-D modeling, and modeling algorithm research.

XINGLI ZHANG received the master's degree in computer software and theory from the Taiyuan University of Technology, in 2005, and the Ph.D. degree in computer software and theory from the Shandong University of Science and Technology, in 2010.

She is currently an Associate Professor with the Shandong University of Science and Technology. Her main research interests are microseismic signal analysis and processing, and deep learning algorithm.

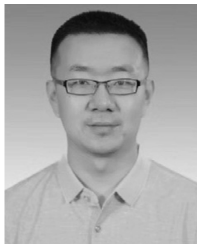


LONGQUAN ZHOU was born in Tai'an, Shandong, China, in 1988. He received the M.S. and Ph.D. degrees from the Shandong University of Science and Technology, in 2015 and 2019, respectively.

He is currently a Lecturer with the Department of Information Engineering, Shandong University of Science and Technology. His main research interests include computer graphics and computational geometry.

XINMING LU received the Ph.D. degree from the Institute of Applied Mathematics, Chinese Academy of Sciences, in 1994.

He is currently a Professor and a Ph.D. Supervisor with the Shandong University of Science and Technology. His main research interests are digital mining, digital city, and digital power. He is also the Taishan Scholar Climbing Plan Expert and the National May Day Labor Medal Winner.



CHONG WANG received the master's degree in software engineering and the Ph.D. degree in mining engineering from the Shandong University of Science and Technology, in 2007 and 2016, respectively. He is currently an Engineer with the Network and Information Center, Shandong University of Science and Technology. He is also a Postdoctoral Fellow with the Beijing Key Laboratory on Integration and Analysis of Large-scale Stream Data.