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A New Collision Detection Algorithm for Vascular Interventional Surgery Simulation Training System

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***Abstract* - In virtual vascular interventional surgery, collision detection between surgical instruments and human soft tissue is the basis for deformation and pressure calculation, and it is also a prerequisite for model cutting. Due to the high calculation and complexity in the virtual vascular surgery simulation process, the existing collision detection algorithms can not satisfy the requirements of real-time and accuracy during surgery. Drawing on the deficiencies and improvements of the soft tissue object collision detection algorithm, and combining the unique characteristics of the soft tissue deformation model, a new soft tissue hybrid collision detection algorithm is proposed. Through the two stages of rough detection and precise detection, a large number of redundant calculations in the original collision detection algorithm are omitted, and the response time of collision detection is greatly reduced. Experiments are compared with the other two algorithms to verify that its real-time performance and accuracy have been improved.**

Index Terms* - *Virtual vascularsurgery, Model cutting, Collision detection, Real-time accuracy

I. Introduction

With the continuous development of contemporary society, people's life pressures have gradually increased, which has also led to the frequent occurrence of various vascular diseases. Minimally invasive vascular surgery is an effective method for these diseases. At the same time, in order to improve the success rate of doctors' surgery, the vascular interventional surgeon training system came into being and became a powerful assistant system for doctors.

The virtual vascular interventional surgeon training system combines modern medicine, virtual simulation technology and computer graphics. Through the simulation of vascular interventional surgery, it provides a more realistic training environment for a large number of interns. On the basis of ensuring safety, the virtual vascular interventional surgeon training system should provide sufficient authenticity for the surgical process, and should also enable the doctor to control the movement of the tool naturally and instinctively, and make full use of the feel and response ability obtained by the exercise to give full play to it. Proficient surgical skills. This requires the system to have a high sense of presence. Among them, force feedback is an important indicator that reflects the authenticity of the training system, and an important prerequisite for accurate force feedback is that there must be a high-precision collision detection technology to detect whether the guide wire and the catheter collide[1].

Collision detection technology exists in the entire surgical simulation process. Accurate and rapid collision detection algorithms play a key role in improving the realism and real-time performance of surgical simulation. The collision detection process is a prerequisite for judging the deformation and cutting of human soft tissues. The collision detection provides important data information for the deformation of the model. Therefore, improving the speed and accuracy of the collision detection process is a prerequisite for ensuring the authenticity and real-time performance of the surgical simulation system.

Collision detection algorithms for different spatial structures include space division and hierarchical bounding boxes[2]. Both of them improve the detection speed by reducing the number of geometric primitives that intersect the number of objects tested. However, the spatial division method realizes the entire simulation scene through hierarchical fine-division technology, and the hierarchical bounding box realizes the scene by constructing a hierarchical bounding box for each object. There is no difference between the advantages and disadvantages. The former mainly focuses on reducing the object pairs that may collide, and the latter mainly focuses on reducing the time complexity of the intersection test of the object pairs that may collide.

Because the hierarchical bounding box can quickly remove the geometric primitives that are unlikely to collide through the intersection test between the bounding boxes, so as to achieve the purpose of reducing the calculation amount of the intersection test. Moreover, its construction is easy, the intersection test speed and update speed are fast, so this paper constructs the collision detection algorithm based on the hierarchical bounding box[3].

II. OverView of The training system

A. System Overview

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The vascular interventional surgeon training system in this laboratory is mainly composed of two parts: the master-slave system of the vascular interventional surgeon training system and the VR(Virtual Reality)-based vascular interventional surgeon training system. The following mainly introduces the part of the training system for vascular interventional surgeons based on VR.

The VR-based vascular interventional surgeon training system uses virtual reality technology and real human body CTA(CT angiography) data to three-dimensionally reconstruct the human body's blood vessel model to build a virtual environment. The virtual environment side relies on the catheter and guide wire operation information of the trained doctor on the master manipulator[4]. In the virtual environment, the corresponding catheter and guide wire move in the simulated blood vessel, and use collision detection and physics engine to simulate the operation of the surgical instrument in the blood vessel.The tactile feedback force received in the media is fed back to master manipulator, so as to provide the doctor with tactile feedback. At the same time, the virtual environment side directly displays various visual information on the display, providing intuitive visual feedback to the trained doctor.

In the previous research of our team, the vascular interventional surgery training platform was built and continuously improved, and its structure diagram is shown in Fig. 1. In 2014, the team designed a manipulator for the vascular interventional surgery training system, which uses magnetorheological fluid to achieve tactile feedback. In 2016,a VR vascular interventional surgery training system based on OpenGL was designed for catheter operation training. In the same year, a new manipulator that uses electromagnetic force to achieve tactile feedback was designed, and related debugging and experiments were carried out in 2016-2017. From 2018 to 2019, on the basis of previous research, the team newly designed a manipulator with catheter guidewire operation, and developed a vascular interventional doctor training system based on the catheter guidewire operation[5],[6].

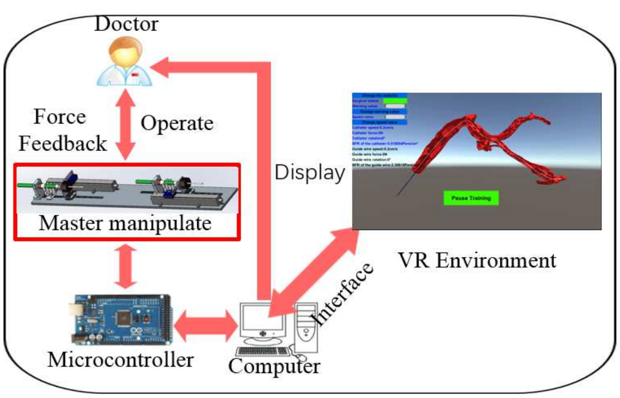


Fig. 1 The concept of the developed training system

B. *Virtual environment platform*

This system uses Unity 3D as the virtual environment platform, and its software interface is shown in Fig. 2. Unity3D is a multi-platform comprehensive game development tool developed by Unity Technologies that allows players to easily create interactive content such as 3D video games, architectural visualization, and real-time 3D animation[7],[8]. It is a fully integrated professional game engine. It has a visual editing interface, which is convenient for script editing. The bottom layer supports OpenGL, Direct11 and physics engine, which can well simulate the physical characteristics of objects. At the same time, it uses the object-oriented programming language C# and can be developed in conjunction with the VisualStudio integrated development environment.

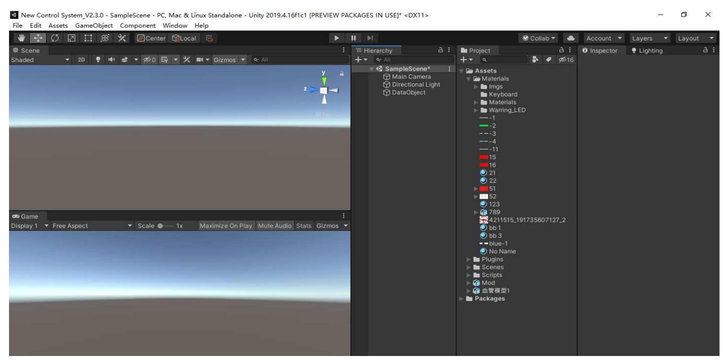


Fig. 2 Schematic diagram of unity3D interface

III COLLISION DETECTION ALGORITHM

At present, the common types of hierarchical bounding boxes include bounding boxes along coordinate axes, spherical bounding boxes, directional bounding boxes, and discrete directional polyhedrons[9]. As shown in Fig. 3.

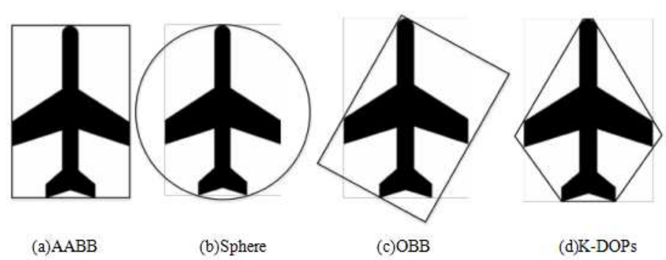


Fig. 3 Commonly used bounding box structure

A. *Bounding box along the coordinate axis (AABB)*

AABB is one of the most widely studied and used bounding boxes in collision detection algorithms. The AABB bounding box is composed of a smallest hexahedron that contains the object and each side is parallel to the coordinate axis, as shown in Figure 3(a) . The calculation of the AABB bounding box of an object is very simple. It only needs to calculate the maximum and minimum values of the vertices of each element in the set of geometric primitives that compose the two objects in the X, Y, and Z coordinates. To determine whether two AABBs intersect, you only need to determine whether the projection intervals on the three coordinate axes overlap. Therefore, this kind of intersection test requires up to 6 comparison operations.

When the object undergoes translation, rotation, etc., the bounding box changes accordingly and needs to be updated. At the same time, its shortcomings are also more obvious, that is, when an object is on the diagonal of the hexahedral bounding box, many redundant points will be generated and the detection efficiency will be reduced.Suppose, the minimum value of the projection on the coordinate axis of the enclosed object is u_x ,u_y , u_z ,The maximum value is v_x ,v_y ,v_z ,Then the area determined by AABB is represented by a non-empty point set R, and its mathematical expression is:

$$R=\{(x,y,z)\,|\,u_x \le x \le v, u_y \le y \le v_y, u_z \le z \le v_z\} \quad (1)$$

B.*Spherical bounding box (sphere)*

The spherical bounding box is a very simple but at the same time a relatively poor tightness. The method of establishing this kind of bounding box is to use a sphere to contain the objects to be enclosed, as shown in Figure 3(b). Its advantage lies in its simple intersection test. For whether two objects collide, it is only necessary to determine whether the distance between the centers of the spheres containing the two objects is greater than the sum of the radii of the two spheres. If it is greater than, then there is no intersection, if less than, then the two balls intersect. The area determined by Sphere is represented by a set of non-empty points R,Its mathematical expression is:

$$R=\{(x,y,z)\,|\,(x-C_x)^2+(y-C_y)^2+(z-C_z)^2 \le r^2\} \quad (2)$$

Where (C_x ,C_y ,C_z) is the center coordinate of Sphere,r is the radius of the Sphere.

C. *Directional Bounding Box (OBB)*

OBB is defined as the smallest cuboid that can contain objects, and the construction direction of OBB is arbitrarily selected relative to the coordinate axis.The area determined by OBB is represented by a non-empty point set R, whose mathematical expression is:

$$R=\{C+ar_1v_1+br_2v_2+cr_3v_3\,|\,a,b,c\in(-1,1)\} \quad (3)$$

Among them, C is the center of OBB,v_1 ,v_2 ,v_3 is the three directions of the cuboid,r_1, r_2 ,r_3 is the radius in the corresponding direction.

The biggest feature of OBB is that it allows arbitrary selection of directions, which can be selected according to the geometry of the enclosed object, thus having a high degree of compactness. However, selecting the best enclosing direction to construct OBB also causes the difficulty of the algorithm. For objects that deform after a collision, the OBB needs to be rebuilt, resulting in a significant increase in calculation. Therefore, OBB is more suitable for rigid bodies that are not deformed, but not suitable for soft collision detection.

D. *Discrete directed polyhedrons (K-DOPs)*

The definition of the bounding box of a discrete directed polyhedron refers to a convex hull that contains an object and the normal vectors of all faces are in a certain fixed direction(FDH), as shown in Figure 3(d). It can be seen from the figure that the K-DOPs bounding box can surround the object more tightly than other bounding boxes. However, the intersection test between bounding volumes of K-DOPs is more complicated.

Since all bounding boxes of K-DOPs are defined by direction vectors from the same set, the intersection test between K-DOPs can be determined based on each direction vector. There are k/2 pairs of vectors in opposite directions in the set. The maximum extension of K-DOPs on each pair of vectors determines its projection interval on the pair of vectors. A bounding box of K-DOPs can be completely described in these vector pairs. Is determined by k/2 projection intervals on. Therefore, the intersection test between the bounding boxes of K-DOPs can be completed by the overlap test of the projection interval. As long as the projection intervals of the two K-DOPs bounding boxes in a certain direction pair in the set do not overlap, it can be judged that they are not intersecting. If their projection intervals on all pairs of directions in the set overlap, they are conservatively considered to be intersecting.K-DOPs are also called fixed-direction convex hulls (FDH).Assuming that X is a non-empty point set, the expression of the convex hull in the D direction is:

$$FDH_D(X)=(H_D(X))_{d\in D} \quad (4)$$

Where FDH is a pair of collinear and opposite vectors.

E. *Comparison of several types of bounding boxes*

The bounding box structure of the model in virtual surgery affects the accuracy and calculation efficiency of collision detection. As shown in Table I, it is the difficulty of construction and other characteristics to horizontally compare the above several commonly used bounding boxes and summarize their advantages and disadvantages.Where “A” stands for the best and “D” stands for the worst.

TABLE I
PERFORMANCE COMPARISON TABLE

Species	Modeling difficulty	Tightness	Difficulty of detection	Update frequency	Suitable for software
K-DOPs	C	A	C	D	B
Sphere	B	D	A	A	C
OBB	D	B	D	B	D
AABB	A	C	B	C	A

As can be seen from the table, different types of bounding boxes have different characteristics.

IV HYBRID HIERARCHICAL BOUNDING BOX ALGORITHM

In view of the advantages and disadvantages of the above various bounding boxes, some researchers have proposed a hybrid bounding box algorithm, which is to construct a variety of bounding boxes to enclose the required objects. In this way, we can not stick to the shortcomings of a single bounding box, but also make full use of the advantages of different bounding boxes[9]. Thereby improving the overall performance of the bounding box.

A. *Introduction to Hierarchical Surrounding Tree Algorithm*

Hierarchical enclosing tree refers to the use of simple hierarchical bounding boxes to enclose complex objects, and then gradually divide the objects until they are subdivided into geometric primitives (such as triangles), or meet a specific end condition, and continue to enclose them The body surrounds the sub-parts of the object. By constructing a hierarchical tree structure to store the bounding box of the sub-parts of the object, let it gradually approach the real object. The intersection test between objects is achieved by traversing the hierarchical tree[10].

The most important thing for this algorithm is how to construct the hierarchical tree. The construction of the hierarchical tree is generally completed in the initial stage of the program's operation, and there is no need to construct the hierarchical tree during the program's operation[11],[12]. The complex object model is divided into many sub-parts by the hierarchical tree, and at the same time, the bounding box of the sub-parts is continuously constructed, and each sub-part of the object is connected by a tree-type hierarchy. As shown in Fig. 4, the root node of the hierarchical tree is used to store the bounding box of the outermost layer of the object, and the child nodes are used to store the bounding box of the subpart of the object. It is gradually divided through a layer-by-layer recursive method until the node reaches a certain condition[13]. After the end, the primitives that make up the object are usually called leaf nodes. The node not only stores the geometric element information of the sub-part of the object, but also stores the bounding box information of the sub-part. During the intersection test, the tree is traversed through the level of the tree and the bounding boxes of the sub-parts are continuously compared to determine whether the object intersects.

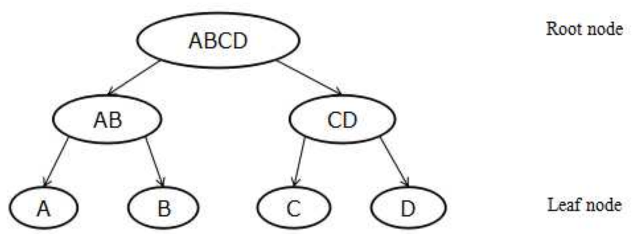


Fig. 4 Schematic diagram of the hierarchical tree structure

B *Construction of Mixed Hierarchy Bounding Box Tree*

This paper chooses to use the binary tree structure to construct the hierarchical bounding box tree, because the binary tree structure is simple, the calculation speed is fast, and it has an efficient traversal method[14].This method will greatly improve the efficiency of collision detection and improve the real-time performance of the system. Construct a bounding box hierarchical tree for the set X of basic geometric elements that compose the object. The methods mainly include three types of bottom-up, top-down, and progressive insertion algorithms[15]. As shown in Fig. 5, it is a schematic diagram of the construction process of the three types of algorithms.

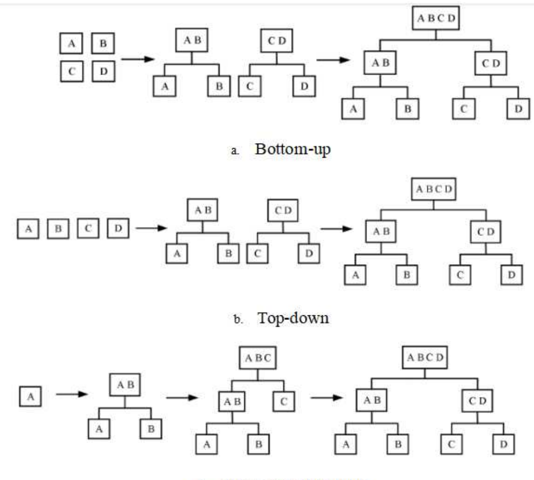


Fig. 5 Constructing methods of three levels of bounding box tree

(1) The bottom-up construction idea is to merge several sets into a parent set. First, create a bounding box for each basic geometric element of set X, which is the leaf node of the bounding box tree, and then use local information to pair the bounding box The leaf nodes around the tree are recursively classified to form a parent node, and so on, step by step up to the root node (set X).

(2) The idea of top-down construction is to divide the complete set into several subsets. First, construct the bounding box with the complete set X as the root node, and then use the information based on the complete set to recursively divide the root node into several subsets, and divide each subset The constructed bounding box serves as the child node up to the leaf node.

(3) The progressive insertion method construction algorithm is a dynamic algorithm for constructing the enclosing tree. By judging the position of the basic geometric elements in the binary tree one by one, the bounding box of each geometric element is inserted into the bounding box tree, and then constructed layer by layer Tree structure.

Although the bottom-up construction method can construct a relatively better binary tree structure, it is difficult to reasonably allocate graphics elements and is poor in feasibility. When the progressive insertion algorithm constructs a binary tree, a large number of location selection operations are very time-consuming and consume space and memory, so there are fewer applications. In contrast, the top-down approach is more mature, easy to implement, and more efficient. Therefore, in the collision detection module of virtual surgery, this paper uses a top-down algorithm to construct a hybrid hierarchical bounding box tree for soft tissues.At the same time, combining the advantages and disadvantages of the above several collision bounding boxes, this paper proposes a hybrid hierarchical bounding box of AABB and K-DOPs. This kind of bounding box mainly combines the characteristics of fast update detection speed of AABB bounding box and good tightness of K-DOPs bounding box to improve the authenticity and real-time performance of doctors during virtual training surgery.As shown in Fig. 6, it is a schematic diagram of the AABB-K-DOPs hybrid bounding box hierarchical tree constructed by the top-down algorithm[16].

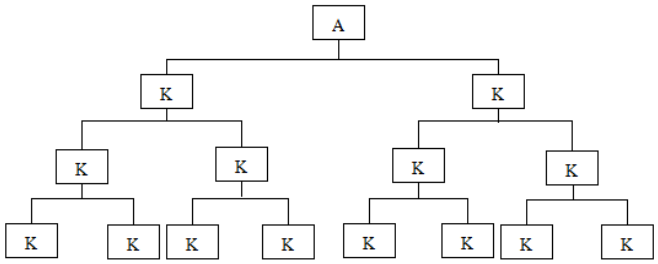
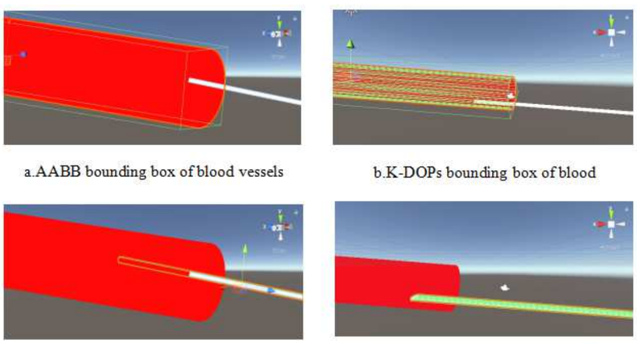


Fig. 6 Hybrid hierarchical bounding box based on AABB and K-DOPs

This paper takes the virtual vascular interventional surgery model as an example to construct a hybrid hierarchical bounding box tree from top to bottom, as shown in Fig. 7. First, construct the AABB bounding box to form the root node of the vascular guide wire model, and then divide the model from top to bottom to establish the K-DOPs bounding box to form the child nodes. As shown in Figure 7a-7d.


a.AABB bounding box of blood vessels   b.K-DOPs bounding box of blood

c.AABB bounding box of guide wire   d.K-DOPs bounding box of guide wire

Fig. 7 Hybrid hierarchical bounding box tree of blood vessel and guide wire

C *Implementation of collision detection algorithm*

This paper mainly studies the collision detection between soft tissue and surgical instruments, which is to complete the collision detection between the blood vessel and the guide wire. After the guide wire is established, the bounding box tree will replace the guide wire for collision detection, and the bounding box tree of the blood vessel will replace the blood vessel collision detection. The specific algorithm is implemented as follows:

(1) First, check whether the root node of the guide wire and the root node of the blood vessel intersect. If the two root nodes do not intersect, it means that the two objects have not collided. Then the collision detection ends, and it is concluded that there is no collision between the two objects. The conclusion of the collision. If the two root nodes intersect, proceed to the second step.

(2) Traverse the bounding box tree of the guide wire and the bounding box tree of blood vessels. It traverses from the root node of the two objects until all child nodes are traversed. If the intersection of the child nodes has never been detected, the collision detection ends, and the conclusion that the two objects have not collided; if the intersection of the child nodes is detected, the collision information such as the collision point is recorded, and the information is output.

According to the above collision detection algorithm, draw the collision detection flowchart, as shown in Fig. 8.

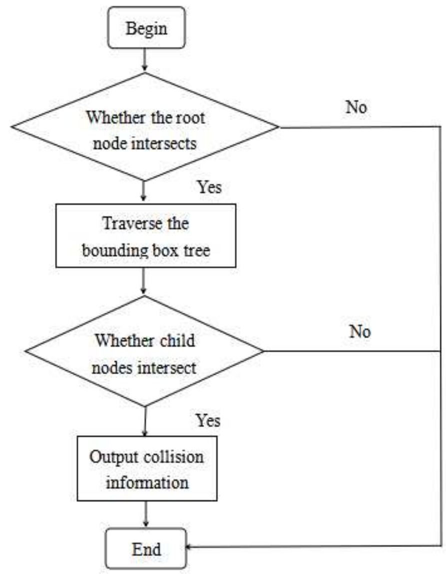


Fig. 8 Intersection test flow chart

V. EXPERIMENTAL RESULTS AND ANALYSIS

The hybrid hierarchical bounding box proposed in this paper is mainly developed based on Visual Studio 2012.The blood vessel and guide wire model established in the virtual system. The blood vessel model contains 18.4k triangular faces and 10.8k vertices, and the guide wire model contains 1.3k triangular faces and 0.9k vertices.At the same time, a simplified vascular guide wire model was made, and the number of triangles and vertices were 2.1k, 1.6k; 0.9k, 0.6k, respectively.

Fig. 9 shows the comparison of the collision detection time of each method. It can be seen from the figure that compared with the K-DOPs bounding box, the AABB and K-DOPs hybrid hierarchical bounding box method greatly improves the detection efficiency and also improves the real-time performance of collision detection.

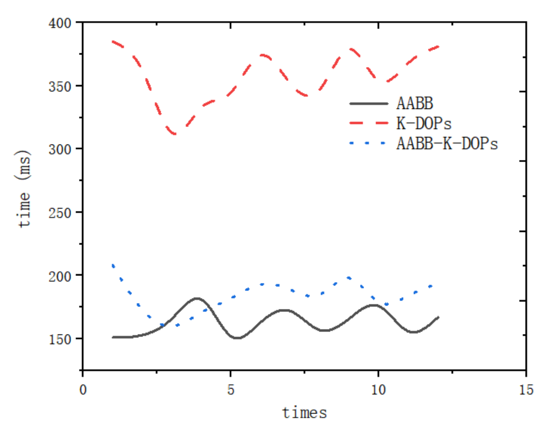


Fig. 9 Collision detection time comparison

Table II shows the comparison of the accuracy of collision detection between the vascular guide wire model and the simplified vascular guide wire model. It can be seen from the table that the accuracy of the AABB-K-DOPs bounding box is close to that of the K-DOPs bounding box. Compared with the detection accuracy of the AABB bounding box, the accuracy of the AABB-K-DOPs hybrid bounding box is significantly improved.

TABLE II
ACCURACY COMPARISON TABLE

Detection object / Collision detection algorithm	Blood vessel and guide wire model	Simplified blood vessel and guide wire model	Average collision detection accuracy rate
AABB	58.33%	66.66%	62.49%
K-DOPs	91.66%	99.78%	95.72%
AABB-K-DOPs	92.36%	99.12%	95.74%

VI. Conclusion

This paper analyzed the advantages and disadvantages of various collision detection algorithms, and determines the use of hierarchical bounding box methods for collision detection between blood vessels and guide wires. Based on the advantages and disadvantages of the four types of bounding boxes and their applicability, a collision detection algorithm based on AABB and K-DOPs with mixed hierarchical bounding boxes was proposed. At the same time, the comparison of experimental results proved that the algorithm can greatly improve the speed and accuracy of collision detection between blood vessels and guide wires.

Acknowledgments

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