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A Review of Collision Detection Technology in Virtual Environment

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ABSTRACT

This paper is a review of collision detection technology in virtual environment. First, it introduces the background and significance of the research, and the research status at home and abroad. Second it makes a comprehensive analysis and in-depth research of various collision detection algorithms. The real-time performance, accuracy and application fields of various collision detection algorithms are discussed. Then it also introduces our main research work on collision detection. On the basis of summarizing the characteristics and limitations of existing collision detection algorithms and aiming at the existing problems of collision detection technology, we propose a set of new collision detection algorithms with good performance. Finally, we give the possible development direction of collision detection technology.

Keywords: Collision Detection Technology, algorithm, real-time, accuracy, Virtual Environment

INTRODUCTION

As a classical problem in computational geometry, computer animation, simulation robot and other fields, collision problem in virtual environment has attracted much attention for many years. The complexity and real-time of virtual environment have put forward higher requirements to collision detection. This paper introduces in detail the research background and significance of the field of collision detection, the research status at home and abroad and the main collision detection algorithms. We also introduce our main research work on collision detection. On the basis of summarizing the characteristics and limitations of existing collision detection algorithms and aiming at the existing problems of collision detection technology, a set of new collision detection algorithms with good performance are proposed. Finally, we give the possible development direction of collision detection technology.

RESEARCH BACKGROUND AND SIGNIFICANCE

Collision detection has a very wide range of practical application value. Collision detection technology is a subject worth studying, whose research results are very rich. With the continuous development of computer graphics and the emergence of new fields, including virtual reality, the requirement of collision detection in practical application is getting higher and higher. Real-time and accurate detection of these collisions plays an important role in improving the authenticity of the virtual environment and enhancing the immersion of the virtual environment. Usually, virtual environment is composed of hundreds of models of objects. When these virtual objects are distributed and simulated, on the one hand, collision detection technology is needed to ensure their physical authenticity, such as one object can not "intrude" into another object. On the other hand, collision detection technology is needed to solve the problem of motion planning and collision avoidance so as to ensure successful dynamic simulation. The complexity of collision detection technology in virtual environment lies in five aspects:

1.High time complexity in dynamic environment

2. Ability to deal with non-convex objects

3.Computation of Accurate Collision Information

4. Ability to deal with large-scale and complex scenes

5. Continuous Updating of Object State

RESEARCH STATUS AND MAIN ALGORITHMS AT HOME AND ABROAD

In recent years, scholars at home and abroad have done a lot of meaningful work in the field of collision detection

and put forward some efficient detection methods. These methods can be divided into static collision detection algorithm, discrete collision detection algorithm and continuous collision detection algorithm from the perspective of time domain. They also can be divided into collision detection method based on entity space and collision detection method based on image space from the perspective of space domain,. For the methods based on entity space, they can be divided into two categories according to the different models of entity: the first is space Decomposition based on BSP (Binary Space Partitioning) tree, k-d tree and Octree; the second is space Decomposition based on hierarchical bounding volume tree. Hierarchical bounding volume tree method can be divided into bounding sphere hierarchical tree, axial bounding box hierarchical tree, directional bounding box hierarchical tree, k-DOP (Discrete Orientation Polytope hierarchical tree, convex hull hierarchical tree and mixed hierarchical tree and so on. The following focuses on the research status of these kinds of collision detection algorithms.

3.1. Collision Detection Technology Based on Time Domain

1 . Static Collision Detection Algorithms

It is an algorithm used to detect collisions between objects in the static state when the objects in the scene do not change on the whole time axis T. Static detection has been widely studied in the field of computational geometry. Generally, there is no real-time requirement for the algorithm. Such algorithms are not suitable for dynamic virtual environments.

2. Discrete collision detection algorithm

Discrete collision detection algorithm is an algorithm that continuously detects collisions between all objects in the scene at each discrete point of the time axis. Essentially, discrete collision detection algorithm can be implemented at every discrete point by a method similar to static collision detection algorithm, but it pays more attention to the efficiency of the algorithm. Due to the discrete time characteristics of the algorithm, there are at least two problems in this kind of algorithm from the whole time axis: (1) there is a piercing phenomenon. When the time step is too long, the two objects may have penetrated at a certain depth before the collision can be detected, so the authenticity of the motion of the object can not be guaranteed; (2) the collision will be omitted. For a narrow object, when the two positions of the moving object at the adjacent time discrete point are exactly on two sides of the narrow object, the discrete algorithm will can't detect the collision of the object correctly.

3. Continuous collision detection algorithm

Continuous collision detection algorithm is an algorithm to judge whether a moving object intersects with other object in a continuous time interval $[t_{n-1}, t_n]$. There are many moving objects in virtual environment. In order to meet the needs of real tasks in dynamic environment, continuous dynamic collision detection algorithm is needed.

Continuous collision detection algorithm can solve the above two problems of discrete collision detection algorithm well, but usually the calculation speed is slow. It cannot achieve real-time collision detection especially in large-scale scenarios, which often becomes the bottleneck of real-time system calculation. Therefore, How to effectively combine the advantages of discrete collision detection algorithm and continuous collision detection algorithm is a new research direction.

3.2 Collision Detection Technology Based on Space Domain

From the point of view of space domain, it can be divided into two kinds: entity-space-based collision detection method and image-space-based collision detection method. The main difference between these two kinds of algorithms is whether to use the three-dimensional geometric characteristics of the object to calculate intersection or to use the two-dimensional projection image of the object plus depth information for intersection analysis.

3.2.1Collision detection method based on image space

The collision detection algorithm based on image space can effectively utilize the drawing acceleration function of graphics hardware to improve the efficiency of collision detection algorithm. In recent years, the performance of

graphics acceleration card has been improved rapidly with the rapid development of graphics hardware technology. Programmable functions have even appeared, which make the collision detection algorithm based on image space enter a new stage of development.

This kind of algorithm has the following advantages:

1. It can effectively reduce the computational load of CPU by using graphics hardware acceleration technology, so as to improve the efficiency of the algorithm;
2. The algorithm itself is insensitive to the complexity of the scene and suitable for collision detection between complex objects;
3. For the same complex scene, the collision detection time changes little and has high stability. It is helpful to predict the collision detection process.

However, image-based collision detection algorithms also have three defects:

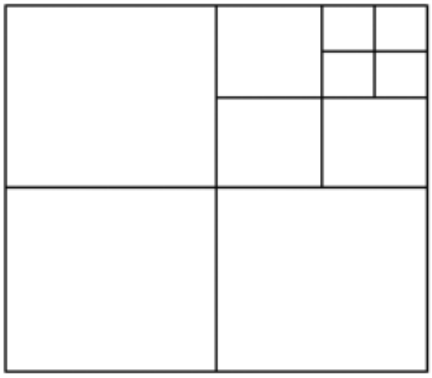
1. Because the image itself is spatially discrete sampling, its accuracy is constrained by the image resolution, which affects the accuracy of the collision detection algorithm;
2. Most algorithms can only deal with the collision detection between convex bodies;
3. Because of the use of graphics hardware-aided computing, image-based collision detection is necessary to consider how to reasonably balance the computational load of CPU and graphics hardware.

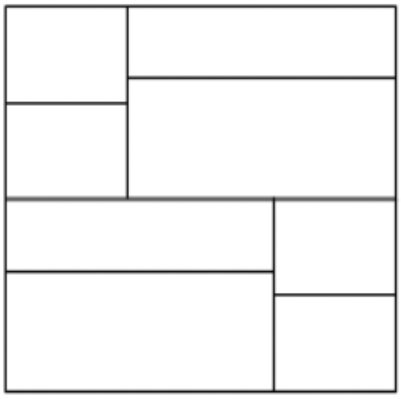
3.2. 2Collision detection algorithm based on entity space

Researchers have applied various geometric techniques such as hierarchical representation, geometric reasoning, algebraic normal form, space division, analytical method and optimization method to collision detection, and proposed many excellent algorithms. The space division algorithm and clipping algorithm are excellent initial detection algorithms for complex scenes with multiple objects. The other algorithms such as feature-based algorithm, simplex-based algorithm, hierarchical bounding tree-based algorithm, distance field-based algorithm and intelligent optimization technology-based algorithm are all based on discrete collision detection technology for two object collision refinement step by step.

1. Space Division Algorithm

Space division method divides scene space into small units according to some rules, and stores a list of objects in each unit to record all objects belonging to this unit. Collision detection only needs to query the intersection of objects in the same unit or adjacent unit (unit with common boundary or vertex), because the objects in the non-adjacent unit are far away from each other and are not easy to collide. If the characteristics of the collision come from the same object, then the self-collision of the object can be detected. Space division algorithm needs to be updated when an object moves or deforms, that is to say, it must reset the list of objects for each unit before detecting each time slice. The commonly used structures are octree ,Kd-tree and BSP tree.





Spacedivision algorithm can effectively reduce the number of object pairs detected in detail, but it is difficult to maintain a consistent detection efficiency when dealing with different scenes and objects with different shapes and complexities, so it is usually used in collision detection in static scenes.

2. Collision detection algorithm based on distance field

It is also a common collision detection method to

establish the distance field of objects for intersection test. Distance field is a basic graphical model in computer graphics. It was initially used for volume drawing and offset surface calculation. As a vector field, the distance field represents the shortest distance from any point in space to the surface of a given object. The distance can have a symbol, indicating whether the point is outside or inside the object. For a closed object, the exterior or interior of the object can be represented by the positive and negative symbols of distance. In collision detection based on distance field, collision detection between different objects is carried out point by point. The collision detection between points and objects can be determined by calculating the distance between them. If $D(p) \prec 0$, collision will happen.

The advantage of collision detection method based on distance field is that it can directly return collision information such as puncture depth and surface normal vector. The bottleneck of distance field method is the construction and update of field. Although many acceleration algorithms have been proposed at present, the speed is not enough to meet the real-time needs.

3. Feature-based collision detection algorithm

This kind of algorithm calculates the distance between two convex polyhedrons by finding and tracking the nearest point between them. When the distance is less than or equal to zero, they collide. When the moving speed of the object is not very fast, the displacement of the moving object between adjacent frames changes little, and the distance between objects does not change much, so the continuity between frames can be used to calculate incrementally. The disadvantage of this algorithm is that it can't deal with concave model.

4. Collision detection algorithm based on simplex

Simplex-based collision detection algorithm was first proposed by Gilbert, Johnson and Keerthi and named by their names, namely GJK algorithm. The principle of GJK algorithm is that two objects are regarded as a simplex, and the separation or penetration distance between them is calculated by the geometric characteristics of the simplex. The main advantage of GJK algorithm is that it can't only detect whether two objects intersect, but also return the penetration depth.

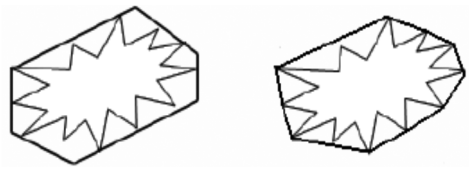
In 2004, the SOLID (Software Library for Interference Detection) algorithm developed by Bergen et al. is also based on GJK. In addition to the basic idea of GJK, it combines the incremental elimination technology based on sweeping and clipping of the axially bounding box. By caching the separation axis of the object pair in the previous frame, the potential intersecting object pairs are identified by the coherence of the frame and the frame to speed up the algorithm efficiency.

5. Bounding Box Hierarchical Tree Collision Detection Algorithms

The core idea of bounding box method is to approximate the complex geometric objects by using bounding boxes with a slightly larger volume and simple geometric characteristics, so as to estimate roughly whether the two detected objects collide by judging whether the bounding boxes overlap or not. Firstly, it detects whether the bounding boxes of the two objects intersect. If they do not intersect, it means that the two objects do not intersect. Otherwise, the two objects are further detected. Because finding the intersection of bounding boxes is much simpler than finding the intersection of objects, many disjoint objects can be eliminated quickly, thus speeding up the detection algorithm.

The selection of bounding boxes is the key point of this method. Typical bounding boxes are AABB (Axis Aligned Bounding Box), Sphere, OBB (Oriented Bounding Box), as shown in Figure below.

In addition, there are k-DOP (Discrete Orientation Polytopes) bounding box, Fixed Direction Hull, etc. The figure is a two-dimensional projection diagram of these two bounding boxes.



The feature of bounding box hierarchical tree collision detection algorithm is that it is simple and efficient, but the disadvantage is that the accuracy is not enough.

COLLISION DETECTION BASED ON INTELLIGENT OPTIMIZATION TECHNOLOGY

With the development of artificial intelligence technology, some novel optimization algorithms, such as artificial neural network, genetic algorithm and particle swarm optimization, have been developed by simulating or revealing some natural phenomena or processes. The unique advantages and mechanisms of these algorithms have aroused widespread attention and research upsurge of scholars at home and abroad, and have been successfully applied in many fields. Collision detection is one of them.

Some researchers put forward a collision detection algorithm based on genetic algorithm between convex polyhedrons. This paper mainly discussed the calculation method of the shortest distance in collision detection. Examples show that the genetic algorithm has fast calculation speed and high calculation accuracy, and it has high feasibility in solving such problems. The disadvantage is that it is only suitable for collision detection between convex polyhedrons.

Recently, a random collision detection algorithm based on particle swarm optimization was proposed by scholars. This method transforms the collision detection problem of objects in three-dimensional space into an optimization problem in two-dimensional discrete space, and then uses particle swarm optimization algorithm to solve it. Their algorithm can guarantee certain efficiency, and also can deal with collision detection between polyhedron models of arbitrary shape. It has good generality. However, the algorithm can not guarantee to find all the collision feature pairs, and the speed and accuracy of the algorithm need to be further improved.

There are many intelligent optimization algorithms, but the methods suitable for collision detection need to combine the existing technology based on geometric space or image space according to the characteristics of the collision detection problem to achieve the final satisfactory results. Therefore, how to use these intelligent optimization tools in collision detection to deal with tens of thousands of levels, hundreds of thousands of levels or higher of complex scenarios is a research direction worth exploring.

Our main research work

Various kinds of collision detection algorithms are comprehensively analyzed and studied in this Paper. On the basis of summarizing the characteristics and limitations of existing collision detection algorithms, and aiming at the existing problems of collision detection technology, a new set of collision detection algorithms with good performance are designed, implemented and verified. Our main research work and achievements are as followsÿ

1. A new algorithm for dividing arbitrary polyhedrons into a series of tetrahedrons is proposed. On this basis, the idea of parallel is introduced to realize parallel collision detection. Thus, the collision detection between two complex polyhedrons is transformed into a series of parallel collision detection between tetrahedrons. On the premise of ensuring high accuracy, the real-time requirements of collision detection are effectively met, and the shortcomings of the general collision detection algorithm which only applies to convex polyhedrons are solved. A parallel collision detection algorithm based on bounding box is completed.
2. A new parallel collision detection algorithm based on particle swarm optimization (PSO) is proposed. The algorithm transforms the collision detection problem into an optimization problem in the space composed of feature pairs of two models, and intelligently optimizes the search characteristics of PSO to complete the search process of local minimum feature pairs in the collision detection process. Combined with the polyhedron partition algorithm, the optimization model is fully parallelized, and then the particle swarm optimization algorithm is used to solve the problem in parallel. The algorithm not only inherits the advantages of collision detection algorithms based on intersection, but also breaks through their limitations. It can deal with collision detection between the arbitrary polyhedrons guaranteeing efficiency. Parallel technology is introduced, and the detection speed can be improved by adjusting the number of nodes.
3. A new parallel collision detection algorithm based on genetic algorithm is proposed. The algorithm transforms the intersection problem of polyhedral models into a linear programming problem with constraints. The evolution process is divided into

different computing nodes and processed in parallel. After dealing with the constraints, excellent genes are exchanged through a certain strategy of information exchange among populations to solve the intersection problem of polyhedral models and to achieve collision detection algorithm. Compared with the traditional methods, the parallel collision detection algorithm based on genetic algorithm not only improves the speed of collision detection, but also guarantees high accuracy, and is suitable for real-time dynamic collision detection between the arbitrary polyhedrons.

FUTURE RESEARCH DIRECTION OF COLLISION DETECTION TECHNOLOGY

In this paper, various collision detection algorithms in virtual environment are studied in detail, and some new collision detection algorithms are proposed to improve the speed of collision detection. However, some work needs to be further improved, which is also the future research direction of collision detection technology.

1. At present, Objects in virtual environment are represented by polyhedrons models. Parallel collision detection algorithm based on polyhedron dividing only applies to objects represented by polyhedron. How to divide objects represented by other models to realize parallel collision detection needs further study.
2. Most algorithms have successfully implemented dynamic collision detection in known environments, but they have not yet achieved dynamic modeling, that is, collision detection in unknown environments needs to be completed in depth.
3. There are many objects in the virtual environment. The forms of motion of various objects are diverse and the changes of motion are complex. The establishment of various complex equations of motion needs further discussion.

CONCLUSION

The main content of this paper is a review of collision detection technology in virtual environment. Various kinds of collision detection algorithms are comprehensively analyzed and deeply studied. The real-time performance, accuracy and application fields of various collision detection algorithms are discussed. We also introduce our main research work on collision detection. On the basis of summarizing the characteristics and limitations of existing collision detection algorithms and aiming at the existing problems of collision detection technology, we propose a set of new collision detection algorithms with good performance. Finally, we give the possible development direction of collision detection technology.

BIOGRAPHICAL NOTES

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She received her PhD from Shanghai University. Her research interest is in the areas of artificial intelligence, robotics and parallel technology.

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