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A Three-layer Hybrid Bounding Volume Hierarchy for Collision Detection

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The Real-time collision detection (CD) is an important problem in virtual environments. This paper proposes a novel algorithm called SBBK which combines three different kinds of bounding volumes (BVs) together when constructing the hybrid bounding box tree for the object to make CD more accurate and faster. For illustration, CD experiments are carried out to show its advantages. The experiment results show that SBBK has better time performance and accuracy than the single AABB BV algorithm especially in dealing with CD in large-scale and complex environments. The proposed algorithm SBBK can effectively accelerate CD and improve the accuracy and thus can be used to solve CD problem in virtual environment or large-scale, complex environments.

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1. Introduction

In the virtual environment, CD, as a very important component, is widely used in many applications physically based on animation, virtual simulation, 3D-game, human motion simulation, computer aided design and system. A popular approach for accelerating CD is bounding volume hierarchies (BVHs) [1] which have been proved to be a successful acceleration data structure for CD between rigid bodies [2], such as Sphere[3], axis-aligned bounding box (AABB)[4], Oriented bounding box (OBB) [5], K-dop [6]. However, different BVs emphasize different aspects between the detection speed and the accuracy under some special situations. To speed up CD process and increase the accuracy of CD, this paper proposes a different hybrid bounding volume hierarchy (HBVH) [7] algorithm which uses three different kinds of BVs to do the intersection tests at different stages of CD. The proposed algorithm combines advantages of different BVs together to speed up CD and increase the accuracy in the process.

The rest of this paper is organized as follows. Section 2 introduces the bounding volume algorithm and HBVH algorithm. In section3, a three-layer HBVH algorithm is proposed and the complexity analysis of this new algorithm is given. In Section 4, experiment results are given showing that the proposed method does have a better performance in CD especially in large-scale, complex environments than original BV method. Finally, the conclusion and future work are described in Section5.

2. Previous Work

A BV (bounding volume) of a model is a primitive shape that encloses the model to make the CD between two objects become simpler. Classic examples of BV types are Sphere, AABB, OBB, K-dop which have different desired properties. The characteristics of these common BVs will be discussed briefly as follows.

Sphere is defined as the smallest Sphere that contains the object. The collision detection of the Sphere bounding volume is to compare whether the distance of centers of Spheres is greater than the sum of both radiuses, but its tightness is relatively poor and therefore less used.

AABB is the earliest bounding box. It is defined as the smallest hexahedron that contains the object and is parallel to the axis. Because of its simplicity of intersection tests and its better tightness than sphere, it has been widely used nowadays.

OBB is the more commonly used bounding box type. It is the smallest cuboid that contains the object and is arbitrarily relative to the direction of the axis. Because of its arbitrariness of direction, its tightness is better than both AABB and Sphere, and it can greatly reduce the number of bounding boxes involved in intersection tests, but the intersection test between OBBs is more complicated.

K-dop, as a special kind of convex hull which inherits the simplicity of AABB, has the best tightness which can surround the object as close as possible. Correspondingly, its intersection test is the most complicated.

BVH[6] (Bounding volume hierarchy) algorithm is an algorithm by utilizing the knowledge of tree structure. It divides the three dimensional object into a hierarchy of BVs. It first divides the object into many sub-parts. Then, the bounding box is built on each sub-part which corresponds to the node of the tree. Based on BVH, HBVH[7] (Hybrid bounding volume hierarchy) algorithm is proposed. It applies different kinds of BVs to different layers of the tree when building the hierarchy BV tree for the object. The advantage of HBVH is that it can utilize the advantages of different BVs to accelerate the speed of CD test. Commonly used HBVH algorithms are S-AABB[8], S-OBB[9], AABB-K-dop[10]. All of them divide the hierarchy tree into two layers. The upper layer uses the bounding volume which is easy to build, update and is simple in doing the intersection test such as sphere and AABB. In this way, it can quickly remove the disjoint object pairs from the intersection tests. The lower layer usually uses bounding volume which has better space compactness such as AABB, OBB and K-dop to improve the algorithm's accuracy.

3.Three-layer HBVH Algorithm

For HBVH algorithms, (i.e.S-OBB, S-AABB or AABB-K-dop), they are all proved to have a better performance than the single BV algorithms. However, the innovation on combining different BVs in order to lead to a better performance is difficult, but in recent years, a three-layer HBVH algorithm has been proposed. This kind of algorithm tries to combine three kinds of BVs together to get a faster and more accurate performance. To take one of them as an example, HBBCD [11] is a typical kind of three-layer HBVH algorithm. The core of this kind of three-layer HBVH algorithm is to select different kinds of BVs in a more reasonable manner and make the best use of different BVs' advantages.

3.1 A novel three-layer HBVH: SBBK

Based on the idea of three-layer HBVH algorithm, this paper proposes a new HBVH which tries to combine three kinds BVs together. Similar to HBBCD, the algorithm also uses AABB BV in the interlayer and adds a Sphere bounding box at the root node. The difference is in the lower layer. The new algorithm replaces the OBB BV in the lower layer of HBBCD with K-dop BV. Figure 1 shows the tree structure of SBBK.

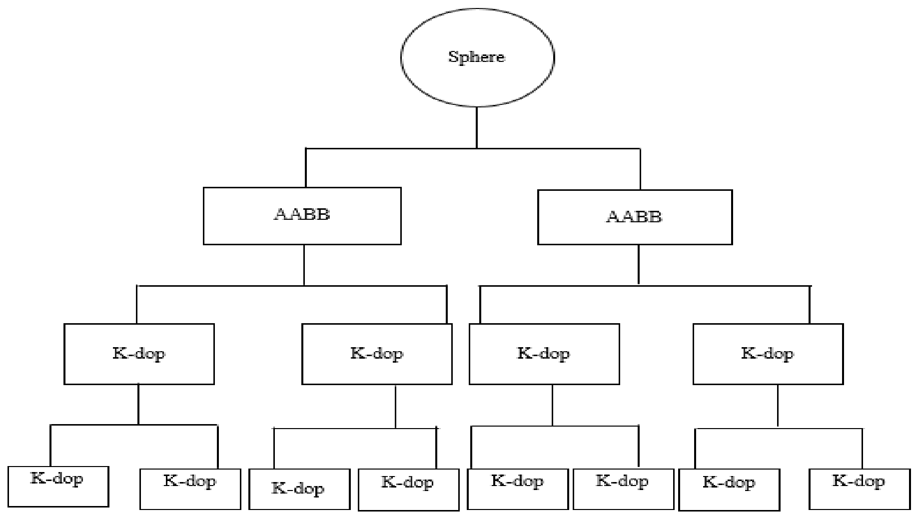
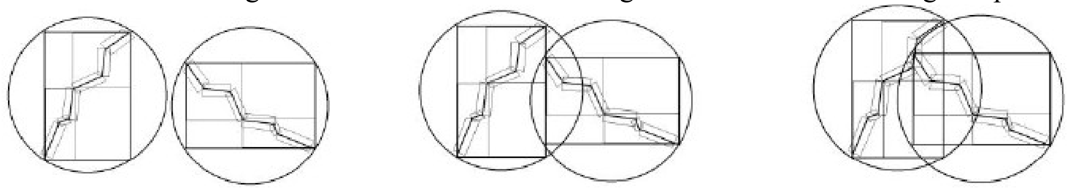


Figure 1: Tree Structure of SBBK

There are three stages in the collision detection. Figure 2 shows the three stages separately.



(a)Initial stage: No contact (b)Rough stage: Shallow contact (c)Accurate stage: Deep contact

Figure 2: Three Stages of Collision Detection in HBVH

For the initial stage (a), the bounding box and object does not collide. Using Sphere BV is simple and enough to exclude those objects, which are far away and disjoint from collision detection. For rough stage (b), to deal with the shallow contact situation, using AABB BV is relatively a good choice. Then for Case (c), to deal with those objects whose bounding boxes are in deep contact, using K-dop BV which surrounds the objects most closely will improve the accuracy.

Compared to the original BV method, the advantages of this new algorithm are as follows:

1. Sphere, AABB and K-dop BV are all suitable for soft body collision detection, but OBB BV is only suitable for rigid body. So replacing the lower layer of HBBCD with K-dop BV allows the new three-layer HBVH algorithm to be applied to soft body detection.

2. K-dop BV has better space compactness. For complicated object, using K-dop BV in the lower layer can enclose the object’s geometric element as closely as possible. For those objects that have a deep collision area, using K-dop BV can lead to a better accuracy.

3. Because of the better tightness of K-dop BV, the hierarchy tree will have less nodes at the lower layer and thus can reduce the number of redundant computing at the intersection detection stage, although the intersection test may be more complicated than OBB BV.

4. As Sphere’s BV intersection test is the most convenient test, using Sphere BV at the root node can quickly determine the possibility of collision between objects. If the Sphere BV at the outermost layer collides, then the object needs to have further intersecting test. Otherwise, the object will not collide and can be removed from the intersection tests. It is the initial stage of collision detection.

5. AABB BV has better tightness than Sphere but worse than K-dop BV. Its intersection test is relatively simple. Therefore, it is a good choice to use AABB bounding box in the upper layer to deal with those objects whose bounding boxes’ contact is relatively shallow or unlikely to collide. This is the rough collision detection stage.

3.2 Complexity Analysis of SBBK

In this section, the research is done on how to traverse the object's bounding box tree to determine whether the object collide or not. At meanwhile, the complexity ananlysis of this new algorithmn SBBK is given.

For simplicity, here we only discuss CD between two objetcs. CD in three or more objects can be decomposed into CD problems between two. Suppose there are two objects to be tested A and B and as well as their respective hybrid bounding box trees a and b. When the outer Sphere bounding boxes intersect between a and b, it is necessary to develop a traversal rule to traverse the nodes of two trees to determine whether they collide or not. Effective and reasonable traversal rules can greatly speed up the traversal speed of the hierarchical tree. For those objects which will not collide, it can eliminate the possibility of intersection earlier, jump out of the tree traversal and speed up the system speed.

This paper combines the simultaneous descent principle and temporal-spatial correlation [12] to solve the problem of node traversal. Simultaneous descent principle, that is, when node A and node B collide, it compares (A→LeftChild, B→LeftChild), (A→LeftChild, B→RightChild), (A→RightChild, B→LeftChild), (A→RightChild, B→RightChild) simultaneously rathan than single dropping on a node through some judging rules.

By comparison, it has been found that the single dropping rule on a node of a hierarchy tree will have $2^{n-1}-1$ tests between internal nodes testing and $(2n-1)2^{n-1}$ tests between leaf nodes and internel nodes, leaf nodes and leaf nodes, totally $2^{2n-1}-1$ intersection tests between nodes. While after using simultaneous descent principle, the number of intersection tests between internal nodes is $(2^{2(n-1)}-1)/3$ and the number of tests between leaf nodes and internel nodes, leaf nodes and leaf nodes is $2^{2(n-1)}$, totally $(2^{2n-1}-1)/3$ tests. It is clearly that using simultaneous descent principle reduces the overall computational effort. When dealing with the intersection tests of hybrid bounding box trees among large-scale complex objects, that is, when n is very large, the acceleration effect is very obvious.

On the other hand, temporal-spatial correlation theory is used to improve the traversal rule. Traditionally, each time the intersection test between trees starts at the root node. However, using temporal-spatial correlation theory here can solve the problem of where to drop rather than start at the root node each time. In the process of objects' moving, the movement of objects is continuous. So the spatial position of the object at this moment is associated with the position at last moment. According to this idea, we can record the intersection test state between two objects of last moment to provide convenience and reference for the next time point's intersection test. To take one tree as an example, Figure 3 shows a tree where red nodes denote the nodes which stop the traversal because of no collsion detected at time t1.

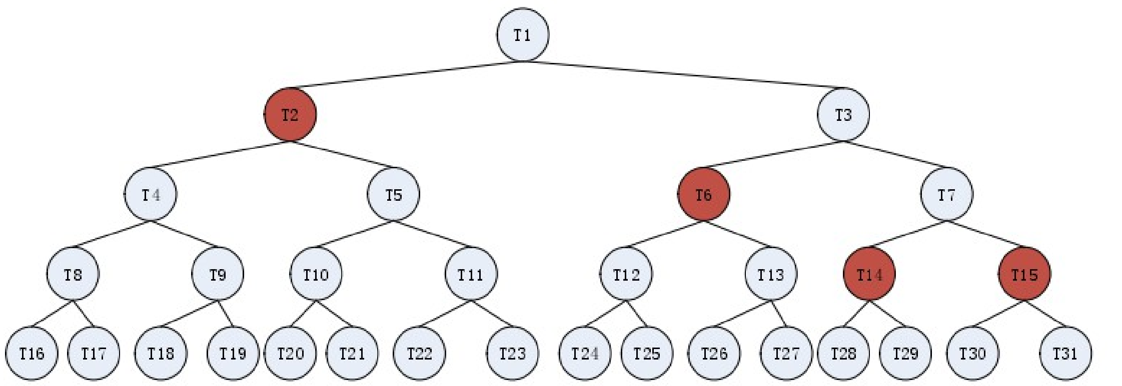


Figure 3: Time t1, Tree Traversal Stops at These Red Nodes

Then, at the next moment t2, the tree traversal for these two trees can start at red nodes marked at time t1 rather than starting at root nodes. Figure 4 shows that tree traversal stops at these green nodes because of no collision detected. If traversal starts at the root node, it needs to access 16 nodes which are T1, T2, T4, T5, T10, T11, T3, T6, T12, T7, T14, T28, T29, T15, T30, T31. If traversal starts at the red nodes marked at t1, it only needs to access 13 nodes which are T2, T4, T5, T10, T11, T6, T12, T14, T28, T29, T15, T30, T31. Assuming that the location of object changes a lot at time t2 compared to last moment t1, traversal starting at red nodes marked at t1 can still traverse to the final leaf node which will have no effect on the traversal result.

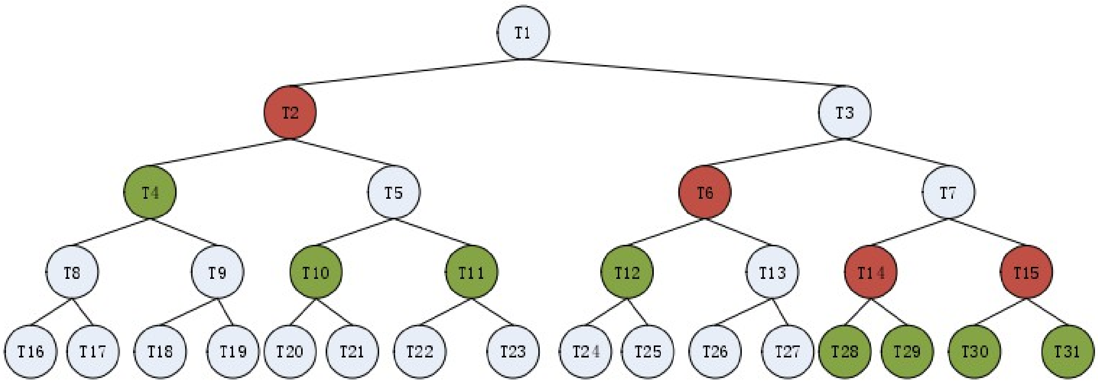


Figure 4: Moment t2, traversal starts at red nodes marked at t1 then updating of the marked nodes

In specific cases, traversal starting at markd nodes of last moment can greatly reduce the work of traversal starting at root node every time. Furthermore, considering how to manage these marked nodes and the problem of traversal order, this paper uses priority queue to store and manage them. It first traverses the nodes that are closer to the leaf nodes. Because these nodes' depth values are larger, so the priority queue can be used to store them and the traversal starts with them first. The time complexity of using priority queue is O(n*log(n)) and it is smaller than that of using linked list which is O(n^2). So the traversal time will be less.

4. Experiment Results and Performance Analysis

4.1 Experiment for Accuracy and Performance

The experiment scenario is created in which it has a helicopter and a small ball. The ball is placed over the helicopter's propeller. The ball falls down due to gravity and collides with the helicopter's propeller. Figure 5 shows the experiment scenario.

Figure 5: Experiment Scenario

In Experiment 1, the hierarchy BV tree is constructed for the helicopter using the new SBBK method. Bycomparison, in Experiment 2, the hierarchy BV tree is constructed using AABB bounding volume. The accuracy comparison is displayed in Figure 6 and Figure 7.

Figure 6: Overlapping Area of Using SBBK

Figure 7: Overlapping Area of Using AABB

The experiment results show that the accuracy of collision detection using single AABB BV is poorer than using the proposed SBBK. In Figure 4 which uses AABB, the overlapping area is larger and can be clearly seen from the picture. While in Figure 3 which uses SBBK, objects are distinguished more accurately, and collision is perfectly detected.

The experiments are all repeated 30 times for the comparison of time-performance. The average frame numbers per second (fps) are recorded in Table 1. The final result shows that using SBBK algorithm can increase the time performance by 11% compared to that by using the AABB algorithm.

Algorithm type	Average FPS
AABB	162
SBBK	180

Table 1: Average FPS of Using Different Algorithms

The difference between the average FPS showing in the above table is very small. In the real experiment, it is hard to tell the fluency difference between two experiments. That is because the number of objects in the experiment is very small. In Section 3, the complexity analysis of the new algorithm is given showing that the new algorithm will have an obvious acceleration effect on CD process when the number of objects in the enviromnet is very large. So another experiment is done to show that SBBK does have a much better time performance among large-scale complex objects.

4.2 Experiment in A Complicated Scenario

To simulate the environment which has large-scale and large number of objects, two thousand monkey heads are placed in the air. When the experiment is running, they will fall down at the same time and collide with each other. The experiment is repeated for two times. The first time, AABB BV is used to build the hierarchy bounding volume tree for each monkey head. The second time, the new algorithm SBBK is used to build HBVH tree for each of them. Each time, the whole time of CD process is recorded. Table 2 shows the time comparison of using different algorithms. The result shows that using SBBK algorithm can increase the time performance by 52% compared to using the AABB algorithm when the number of objects in the environment is very large(n=2000). Figure 8 shows the experiment scenario. Diagram 1 gives a intuitive display of the time difference of using different algorithms when the number of objects in the environment is different.

Algorithm Type	Whole Time of CD
AABB	71.8ms
SBBK	34.5ms

Table 2: Time Comparison by Using Different Algorithms

Figure 8: Experiment scenario of dropping two thousand monkey heads

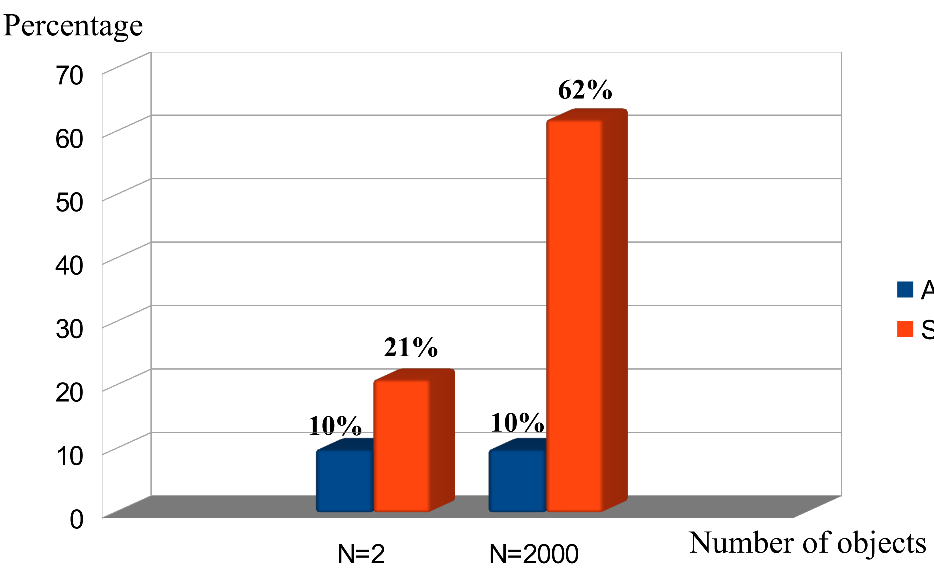


Diagram 1: Time Difference Showing in Percentage Form

From the diagram, it is clear that when n (number of objects) is large, the time improvement by using the new HBVH algorithm SBBK is much better. It also proves that the time complexity of SBBK is correct, because in the complexity analysis, it also clarifies that SBBK will have a much better time performance in large-scale and complex environment, that is, the number of objects is very large.

5. Conclusion

This paper proposes a new three-layer HBVH algorithm called SBBK. It uses a Sphere BV as the root node, AABB BV in the interlayer and K-dop BV in the lower layer. The experiment results show that SBBK has a better performance than the single BV algorithm. It also proves that the new algorithm will have a great advantage in large-scale, complex environmet. In the experiment, the hierarchy bounding box tree is constructed manually. The future work of this paper can be the research on automatically allocating the upper and lower layers of the bounding box tree according to the geometric characteristics of the object to enhance the performance of this algorithm further.

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