Research on Collision Detection in Virtual Measurement Scene

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Abstract. Facing the need of virtual laboratory of engineering drawing, virtual measurement module is developed. According to the collision features, the collision detection algorithm based on OBB hierarchical bounding box method is applied to the virtual measurement scene. A scanning sampling method is used to simulate the dynamic measurement process. As to the sampling point, the means of dividing the value by two points and limiting the step distance is obtained. The method of determining the traversal order by the distance of the center of the bounding box is proposed in the process of traversing the tree to reduce the average lookup depth of the bounding box tree intersection test. Accurate collision detection between STL model [1] and virtual measurement tool using VS2013 and OpenGL. Through experimental verification, the whole process satisfies the accuracy and real-time requirement of the measurement, and proves the validity and fastness of the collision detection algorithm and its optimization method.

Introduction

Virtual laboratory [2, 3] is an open virtual experiment system based on virtual technology, which is a virtual computer-based information integration environment. The main function modules of virtual laboratory of engineering drawing are divided into virtual measurement, virtual assembly and virtual configuration. According to the accuracy and fast requirement of virtual measurement, the strategy of collision detection needs to be studied and improved. Virtual measurement is a dynamic process that realizes real-time and high accuracy continuous collision detection plays an important role in enhancing the immersive and veracity of virtual scene. Since most virtual reality systems require real-time human-computer interaction, only when the speed of continuous collision detection reaches a certain frame number, the human-computer interaction can flow smoothly. Dynamic collision detection is usually achieved by scanning the sampling method, which performs static collision detection at certain points of time on the trajectory of an object.

In this paper, the means of dividing the value by two points and limiting the step distance is obtained to reduce test scan sampling points and avoid the appearance of puncture. Static interference detection algorithm is the foundation of dynamic collision detection algorithm, and the efficiency of static interference detection directly influences the efficiency of the whole algorithm. The collision detection between all the elements in the virtual scene requires accurate test results, otherwise it will produce obvious unreal feeling. The collision detection algorithm applied in this paper satisfies the accuracy and real-time requirement in virtual measurement scene.

The Structure and Intersection Test of the Hierarchical Bounding Box Tree

The Design and Construction of Hierarchical Bounding Box Tree [4, 5]

The bounding box method uses a slightly larger and geometrically simple bounding box to approximate the geometric object. By judging the overlap of bounding boxes, it is possible to quickly eliminate the non-intersecting geometry and detect only the partial objects that overlap the bounding box, so as to raise the detection algorithm speed accordingly. The classical bounding box existing in the hierarchical bounding box collision detection method includes the AABB (Aligned Axis...
Bounding Box), bounding spheres, OBB (Oriented Bounding Box) and k-DOPs (Discrete Orientation Polytopes). The AABB bounding box is first proposed and applied in the rigid body-based collision detection algorithm, but it is not suitable for measurement scenarios because of its poor tightness. The tightness of the sphere bounding box is also insufficient according to the construction and intersection test. The intersection test of OBB is costly, but its tightness is good, the number of bounding boxes involved in intersecting tests and the number of basic geometric elements can be multiplied. Using the surround box to surround the object and intersecting the surround box before testing can significantly improve test efficiency. However, the process of testing has been simplified, the number of tests did not change. The test process remained the same time complexity \( O(n \times m) \) (\( n \) is the triangular face number of the parts, \( m \) is the triangular face number of the measuring tool). The bounding box method is combined with tree structure to solve this problem. Using bounding volume hierarchy (BVH) could significantly reduce the time complexity to log level [6].

Based on the above analysis, the OBB hierarchy tree is applied in this paper.

With regard to the performance of the hierarchical bounding box tree, Klosowski [7] proposed a generic performance test formula which is shown in Eq. 1.

\[
T = N_v C_v + N_p C_p + N_u C_u + C_o
\]  

(1)

\( T \) is the performance of the collision detection between objects, \( N_v \) is the number of bounding boxes tested during the test process, \( C_v \) is the time spent for testing the two bounding boxes, \( N_p \) is the number of primitives to be tested, \( C_p \) is a pair of primitives to detect the time consumption, \( C_o \) is the cost after deformation. Therefore, to improve the performance of the hierarchical bounding box tree, it is necessary to measure the depth of the hierarchical tree and the number of primitives in the leaf node.

(1) The choice of the tree’s degree

This paper chooses the binary tree as a hierarchical tree structure for the following reasons.

The binary tree is the simplest tree structure, the binary tree representation and traversal are convenient. When the degree of the tree is greater than 2, the node segmentation strategy is difficult to determine. In addition, the time in the tree construction process will be greatly increased.

For a balanced binary tree of \( n \) nodes, up to detect \( (d-1) \) nodes in the \( d \) nodes of the current nodes are detected when searching for the child nodes from the root node to the leaf node.

Therefore, as Eq. 2 shows, the time complexity is proportional to the function \( f(d) \):

\[
f (d) = (d - 1) \log_d n
\]  

(2)

Since \( d \) is an integer greater than 1, when \( f (d) \) takes the minimum value, the value of \( d \) is 2.

(2) Node segmentation strategy

In this paper, binary tree is chosen as the data structure of hierarchical tree, so node dissection strategy is to divide a parent node into two sub-nodes. The segmentation strategy is to minimize the volume of the surrounding boxes of the two child nodes and reduce the generation of redundant space. Therefore, it is necessary to balance the number of graphs of the child nodes and the surrounding box characteristics.

The specific method of node segmentation strategy is to select a subdivision plane named the division plane, and divide the nodes according to the position of primitives included in nodes relative to the subdivision plane. For instance, geometrical elements are divided into the left child nodes on the left of the segmentation plane, and the right child node is divided on the right of the segmentation plane (Divide the primitives according to the geometric center). When the center of the primitive is on the segmentation plane, the primitive will be divided into the side with fewer primitives, so that the number of primitives in the child node is not increased and the tree balance is reached [8].

(3) Determination of segmentation plane

The segmentation point and the segmentation axis are required to determine the segmentation plane. Select the direction of the longest side of the three axes of the OBB bounding box as the
segmentation axis [9]. Using the median method to determine the segmentation point, which all the elements are projected onto the split axis, take the median value of the projection can be used as a segmentation point.

(4) Construction termination condition
When the depth of the tree is greater than 15 or the segmented child node contains fewer than 10 primitives, the structure is terminated.

(5) The method of hierarchical tree construction
The main three kinds of constructing hierarchical bounding box tree are top-down, bottom-up and insert method, this paper choose the top-down structure which is relatively easy to achieve and has a faster build speed. The overall structure of the idea as shown in Figure 1.

The node structure of hierarchical OBB tree is:
```c++
struct obbTreeNode {
    OBB obb; // OBB included in nodes
    vector<int> triangle_log; // If the node is a leaf node, it include the triangle face number of corresponding object
    bool is_end; // Marks whether the node is a leaf node
    obbTreeNode* left; // Left node
    obbTreeNode* right; // Right node
};
```

The construction process is shown in Figure 2.

![Figure 1. Top-down construction method.](image)

![Figure 2. Hierarchical OBB tree construction process.](image)
In order to improve the running speed of the program, this paper adopts the method of constructing with offline structure, which could solve the problem of complexity in the construction of hierarchical OBB tree. During operation, the surrounding box tree is updated to speed up the system and improve the system's immersion. The resulting hierarchical OBB tree file format is shown in Figure 3.

![Hierarchical OBB tree file format](image)

**The Intersecting Detection of OBB and Triangle Faces**

The intersecting detection of OBB adopts SAT (Separating Axis Theorem) [10], which is the most commonly used method in collision detection of bounding box. The principle is two convex polygonal objects, if we can find a shaft, so that the two objects on the axis of the projection does not overlap, then there is no collision between the two objects, the axis of the separation axis. For OBB bounding box collision detection in 3D space, it is necessary to calculate 15 separation axes (The three axes of OBB A, the three axes of OBB B, and nine axes perpendicular to the axial combination of the OBB A and B). If there is no overlap of the bounding boxes projection on all separation axes, it is determined as no collision, otherwise the bounding boxes are regarded as collision [11].

The objects in the virtual environment are represented by triangular faces, so the detection of whether the parts and tools are colliding requires detection of the triangular faces. This paper uses Decillers & Guigue algorithm [12], which judges the relative position of geometrical element in triangle faces by determining the geometrical meanings of the negative of determinant which is formed with the triangle’s vertices. The method uses less memory in the calculation process and is less affected by machine error, so that the stability and efficiency of the algorithm are higher.

**The Realization of Virtual Measurement**

The realization of the measurement is based on the fact that two non-penetrating objects cannot share the same space region. This means that parts and measurement tools cannot share the same space, and when the measuring tool touches the parts, it will be stopped precisely.

**Design of Measurement System**

When the measurement system receives the user's control, the measuring tool or part shall be controlled accordingly. In the process, the movement of the parts and tools shall meet the above conditions. The object is in motion, the position of the object is constantly changing with time, so the measurement process is a process of dynamic detection. Due to the complexity of dynamic detection
algorithm and the strategy, in this paper, the scanning sampling method was adopted. The static intersection detection of several undetermined time points on the trajectory of the object is used to simulate the process of dynamic detection with multiple static detection methods. Static detection adopts the method of hieratical OBB tree, which gradually approximates to the object model by establishing the hierarchical OBB tree of objects. The slightly larger but geometric simple bounding box is used instead of complex objects in collision detection, so that the disjoint primitives are easily excluded after the intersection detection of OBBs. Therefore, the number of intersecting times is reduced obviously.

This paper uses binary value to sample static detection points, recursive the process until the left and right boundary spacing is less than the detection accuracy, then return the results. For instance, when users take a displacement of parts of (10, 0, 0), the system will test the static point (5, 0, 0) at first. If there has collision on the point, then test the static point (2.5, 0, 0). This process will recursive until the left and right sides of the boundary reach the setting precision, which is set as 0.01mm in the measurement system. The binary value method can quickly determine whether the tool. What’s more, the collision point will be quickly found when the parts collide.

Puncture occurs when the user's input control span is too large or the thickness of the part is too small, as the Figure4 shown. The too large step will course puncture, whereas too small step will affect the refresh frame rate of the measurement system. Therefore, take into account the thickness of the tool and the parts, the step distance of each sampling is set as 1cm and the maximum puncture thickness is 0.5cm. The users can also set the parameter according to the actual situation.

![Figure 4. Puncture example.](image)

The entire testing process needs to determine whether there is a collision between the tool and the part. If there is no collision, the objects will be controlled according to the user's appropriate input. If the two collide, find out the point which tool and the part just collide at the beginning, then the parts or tools will be controlled to reach the initial contact point. The whole process can simulate the real world objects and make the system have real sense. The method of scanning the sampling points and limiting the step distance is an appropriate way to balance the detection speed and detection accuracy, which is the most basic design idea of the whole system.
The Process of Static Detection

The tool is described as approximate bounding box, as the Figure 5 shown. The approximate bounding box can meet the requirements of measurement accuracy, and can reduce the time complexity from $O(n \times m)$ to $O(n)$ ($n$ is the triangular face number of the parts, $m$ is the triangular face number of the measuring tool).

Figure 5. Bounding box of measurement tool.

The description of parts uses hieratical OBB tree, which generates information offline and updates when a rotational displacement occurs [13]. The program flow is shown in the Figure 6.

Figure 6. Static detection flow chart.
Each of the approximate bounding boxes of the tool is intersecting with the hierarchical bounding box tree of each part until the root node is detected. If the root node is still colliding with the tool, the triangle faces containing in the bounding box of the root node and the tool bounding box will be tested. The method of using a hierarchical bounding box tree reduces the time complexity from $O(n)$ to $O(\log n)$. If a pair of triangular faces intersect, the collision is determined, otherwise there is no collision.

**Experiment and Result Analysis**

**The Results Show**

The measurement module of virtual laboratory of engineering drawing is realized in VS platform with OpenGL, applying the algorithm mentioned in this paper. Users can measure by selecting parts and corresponding tools. The parts library contains a total of 20 complex parts such as bushings, roulette, plate cover, fork and bin. The tool library includes Vernier calipers, inner calipers and external calipers, which can measure the length, inner diameter, outer diameter and depth. The guide interface of the program is shown in the Figure 7.

![Guide interface](image)

Figure 7. Guide interface.

As Figure 8 and Figure 9 show, readings can be obtained by direct observation or program display. The system is able to provide quick and accurate feedback to the user's operations to meet real-time and accuracy requirements.

![Measurement readings](image)

![Measurement results](image)

Figure 8. Measurement readings.  
Figure 9. Measurement results.
Performance Analysis of the Hierarchical OBB Tree

Table 1. Performance analysis of the hierarchical OBB tree.

<table>
<thead>
<tr>
<th>Number</th>
<th>Amounts of faces</th>
<th>Hierarchical OBB tree method</th>
<th>Conventional method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>464</td>
<td>45.14ms</td>
<td>201.81ms</td>
</tr>
<tr>
<td>2</td>
<td>764</td>
<td>80.73ms</td>
<td>301.91ms</td>
</tr>
<tr>
<td>3</td>
<td>1480</td>
<td>289.01ms</td>
<td>685.92ms</td>
</tr>
<tr>
<td>4</td>
<td>2692</td>
<td>433.15ms</td>
<td>1311.14ms</td>
</tr>
</tbody>
</table>

The four parts were tested several times, and the same operation was processed and counted in two ways. Processing data is obtained in Table 1, it can be concluded that the speed of hierarchical OBB tree is nearly three times higher than the conventional method in performance.

Adjust the Traversal Order to Improve the Detection Speed

The efficiency of static detection directly affects the efficiency of the whole algorithm. In the process of traversing the tree, the conventional method is traversing the tree or preorder traversal by level without considering the stacking order of the nodes. However, in the process of traversing, the distance between the child nodes closer to the center of the tool's bounding box is more likely to collide with the tool. Therefore, the stacking order of the child nodes is adjusted during the static detection process. For each node, the further farther node from the center of the tool bounding box in two child nodes will be prefixed to the stack precisely, so that the bounding box with the closer distance can be detected first. If a collision occurs, the collision can be detected more quickly, thus achieving the need to speed up the detection speed.

By experiment, it is concluded that there is no significant improvement in the improved method compared with the conventional method when the static detection does not occur. However, when the detection result is collision, the method has an improvement of 3.106% in speed. The results of experiment are shown in Figure 10 and Figure 11.

Summary

Aiming at the virtual measurement scene, the dynamic detection process of the measurement is realized by using the method of binary static detection point. In addition, the setting of the step distance is used to avoid the occurrence of puncture. The static detection process uses the improved OBB algorithm and processes the measurement tool as the approximate bounding box to reduce the detection process of time complexity.

The system includes Vernier caliper, inner calipers, outer calipers and other measuring tools, nearly 20 complex parts such as box and pump. The algorithm is versatile, and the tools and parts are extensible. The measurement method includes the measurement of length, depth, inner diameter and...
outside diameter. The measurement scene can meet the requirements of real-time and authenticity. In the process of traversing, the stacking order of the child nodes is adjusted according to the distance between the child nodes and the center of tool's bounding box. In the event of a collision, the method has an improvement of 3.106% in speed.

References


