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S-CD: SURFACE COLLISION DETECTION TOOLKIT FOR VIRTUAL PROTOTYPING

Mauro Figueiredo. *Universidade do Algarve.*

ABSTRACT

This paper presents an efficient collision detection algorithm designed to support assembly and maintenance simulation of complex assemblies. This approach exploits the surface knowledge, available from CAD models, to determine intersecting surfaces. It proposes a novel combination of Overlapping Axis-Aligned Bounding Box (OAABB) and R-tree structures to gain considerable performance improvements. This paper also shows an efficient traversal algorithm based on the R-tree structure of Axis-Aligned Bounding Boxes to determine intersecting objects and intersecting surfaces between three-dimensional components, for supporting the recognition of constraints in assembly and disassembly operations in virtual prototyping environments.
The implementation of the proposed collision detection algorithm, known as S-CD (Surface Collision Detection) toolkit, performs well against moderately complex industrial case studies. Current experimental results show that S-CD is effective in determining intersecting surfaces at interactive rates with moderately complex real case studies.

KEYWORDS

Collision detection, virtual prototyping, bounding volume hierarchies.

1. INTRODUCTION

An assembly constraint-based approach is used for simulating physical realism and interactivity for assembly and disassembly operations in virtual prototyping environments [Murray and Fernando 2003]. It relies on a set of geometric constraint relationships that are automatically established or removed as the user manipulates the assembly components. The functional modules used in this approach are collision detection, constraint recognition, constraint satisfaction, constraint management and constraint motion. The automatic constraint recognition process uses collision detection services for various purposes such as (a) to provide collision response to stop object penetration, (b) to identify colliding surfaces to support the recognition of assembly relationships between the assembly parts, (c) to simulate constrained motion, (e) to simulate kinematics motion and sliding, thus assisting users to carry out precise object manipulations.

Real-time recognition of assembly constraints demands an efficient surface-based collision detection algorithm. Virtual prototyping models, generated by Computer-Aided Design (CAD) systems, are surface-based. The recognition of constraints for assembly and disassembly operations relies on the knowledge of the intersecting surfaces. However, current collision detection algorithms for virtual environments are based on polygonal models and determine intersecting polygons, disregarding all the surface data of the CAD model. While these toolkits are useful for supporting physically-based simulation of rigid objects, they do not support the extra functionalities necessary for supporting assembly simulation, based on an assembly constraint-based approach. The awareness of all the colliding surfaces is valuable information to allow the automatic recognition of assembly constraints between surfaces.

This paper presents the S-CD (Surface Collision Detection) toolkit for collision detection in the narrow phase. It determines intersecting surfaces between three-dimensional components, for supporting the recognition of constraints in assembly and disassembly operations in virtual prototyping environments.

The S-CD toolkit uses Axis-Aligned Bounding Boxes (AABBs), the Overlapping Axis-Aligned Bounding Box (OAABB) concept and a hierarchy of R-trees to improve performance of the collision detection process.

The OAABB volume was introduced in [Figueiredo et al 1993] for improving performance in the determination of intersecting polygons. Smith et al [1995] use the same concept but with an octree data structure for finding intersecting polygons. This paper presents new work that extends the OAABB concept for surfaces. This paper also shows the novel combination of OAABB at three different levels: objects, surfaces and triangles. The OAABB is used to reduce: (i) the number of axis-aligned bounding boxes intersections and (ii) the number of bounding volume update operations.

This paper also presents new work using R-trees in the narrow phase for speeding up the collision detection problem. Held et al [1995] implemented a collision detection approach to find collisions of only one moving object in a virtual environment. They use a binary R-tree to represent the static scenario. The approach presented is also novel work with R-trees. It allows any number of moving objects. A novel structure is described where each object is represented by an R-tree data structure at two-levels. First, for each object, an R-tree of surfaces is built, grouping neighboring surfaces. Secondly, the set of triangles that represent each surface is organized in another R-tree structure. The detailed design of an efficient R-tree structure for the collision detection is presented. It is also described a novel traversal algorithm for collision detection that takes advantage of this 3D geometry structure.

Together, the OAABB and the R-tree structures, enables the effective reduction of the number of intersection operations, hence providing considerable performance gains. Results show that the proposed collision detection achieves interactive rates in real industrial applications as desired.

The paper is organized as follows. Section 2 presents related collision detection approaches for the determination of intersecting triangles between two objects. Section 3 presents the design choices and section 4 the implementation of the collision detection algorithm to compute intersecting surfaces between three-dimensional objects. Section 5 presents the evaluation results. Conclusions are presented in section 6.

2. BACKGROUND

Bounding volume hierarchies (BVH) are frequently used to organize the triangles of an object to improve the performance of the collision detection process, by reducing the number of pairs of bounding volume tests. The classic scheme for hierarchical collision detection is a simultaneous recursive traversal of two bounding volumes trees A and B.

Several types of bounding volumes are available. Bounding spheres can be used [Bradshaw and Sullivan 2004]. SOLID [Van Der Bergen 1997] and OPCODE [Terdiman 2001] uses axis-aligned bounding boxes (AABB). RAPID [Gottschalk et al 1996], V-COLLIDE [Hudson et al 1997], PQP [Larsen et al 1999], H-COLLIDE [Gregory et al 1999], use oriented bounding boxes (OBB). QuickCD [Klosowski et al 1998] and Dop-Tree [Zachmann 1998] uses *k*-dops; and Swift++ [Ehmann and Lin 2001] uses convex hulls (CH). There are also hybrid approaches like QuOSPOs [He 1999] that use a combination of OBBs and k-dops.

It is very difficult to compare different approaches since performance also depends on the shapes of the models, type of contact, size of the models and others.

Bounding spheres main advantage is that they are faster to intersect and update. The main disadvantage is that they do not approximate objects tightly.

The main advantage of SOLID, OPCODE and Box-Tree is that AABBs are faster to intersect. When using AABBs, only six comparisons are required to find out if two axis-aligned bounding boxes are overlapping. It is also possible to say that two AABBs are disjoint, in the best case situation, with only one comparison. Another advantage of using AABBs is that it is simple to update these volumes as an object rotates and translates.

RAPID approximates 3D objects with hierarchies of oriented bounding boxes (OBBs). An OBB is a rectangular bounding box with an arbitrary orientation so that it encloses the underlying geometry more tightly. The representation of an oriented bounding box encodes position, widths and orientation. The main advantage of RAPID is that OBBs are better approximations to triangles reducing effectively the number of intersecting operations.

V-COLLIDE solves the broad-phase of the collision detection using a sweep-and-prune operation to find pairs of objects potentially in contact. It uses RAPID to find in the narrow phase which pairs of objects intersect.

PQP solves the narrow phase and is also based on the RAPID library. It uses oriented bounding boxes to find intersecting objects. PQP also computes the distance between closest pair of points using swept spheres.

H-COLLIDE is a framework to find collisions for haptic interactions. It uses a hybrid hierarchy of uniform grids and trees of OBBs to exploit frame-to-frame coherence. It was specialized to find collisions between a point probe against 3D objects.

The QuickCD and Dop-Tree implementations build a hierarchy tree of *discrete orientation polytopes*. Discrete orientation polytopes, or *k*-dops, are convex bounding volumes whose faces are determined by halfspaces whose outward normals come from a small fixed set of *k* orientations. The main advantage of using discrete orientation polytopes is that *k*-dops are better approximations to the underlying geometry than AABBs with the advantage of its low cost compared to OBBs. A major drawback of QuickCD is that allows only one moving object.

Swift++ builds a hierarchy of convex hulls and intersection is tested using a modified Lin-Canny [Lin and Canny 1991] closest feature algorithm.

He [1999] uses a hybrid approach that combines OBBs and k-dops called QuOSPOs. This approach provides a tight approximation of the original model at each level.

Since collision detection is a very demanding task, researchers are also working in using existing graphics accelerated boards (GPU) [Baciu and Wong 2003, Knott and Pai 2003, Govindaraju et al 2003, Yoon et al 2004] or dedicated hardware [Raabe et al 2006] to accelerate collision detection by hardware.

Algorithms using graphics hardware use depth and stencil buffer techniques to determine collisions between convex [Baciu and Wong 2003] and non-convex [Knott and Pai 2003] objects. CULLIDE [Govindaraju et al 2003] is also a GPU based algorithm that uses image-space occlusion queries and OBBs in a hybrid approach to determine intersections between general models with thousands of polygons. MRC [Yoon et al 2004] deals with large models composed of dozens of millions of polygons by using the representation of a clustered hierarchy of progressive meshes (CHPM) as a LOD hierarchy for a conservative errorbound collision and as a BVH for a GPU-based collision culling algorithm.

These GPU-based algorithms are applicable to both rigid and deformable models since all the computations are made in the image-space. Collision detection methods using GPUs have the disadvantage that they compete with the rendering process, slowing down the overall frame rate. Furthermore, some of these approaches are pure image based reducing their accuracy due to the discrete geometry representation.

Collision detection with dedicated hardware acceleration techniques for *k*-dops bounding volumes has been experimented [Raabe et al 2006]. An ASIC and a FPGA collision detection single-chip was developed with two main stages, one for traversing simultaneously a hierarchy of *k*-dops and one for intersecting triangles. The ASIC and the FPGA implementations are up to 1000 and four times, respectively, faster than the software intersection tests on a standard CPU.

3. DESIGN CHOICES

In this research, a 3D object is defined by a collection of surfaces in the three-dimensional space. Each surface is tessellated individually and represented as a collection of triangles.

The time to determine collisions between two objects using BVH depends on: (1) the cost of intersecting and updating bounding volumes; (2) the cost of intersecting triangles; and (3) on the number of such operations.

3.1. Type of Bounding Volume

The choice of bounding volume type influences performance of the collision detection process.

The collision detection toolkit presented in this paper uses axis aligned bounding boxes for four reasons: i) they are fast to intersect; ii) use less memory; iii) hierarchies of AABBs are faster to build; and iv) faster to update, when compared to oriented bounding boxes and discrete orientation polytopes.

Axis-aligned bounding box intersection requires in worst-case six comparisons and theoretically it is three times faster than 18-dops. While the worst-case for intersecting two OBBs requires the execution of 252 arithmetic operations.

Axis-aligned bounding volumes use less memory. An AABB is represented with only six scalars for representing its extents. An oriented bounding box is represented with fifteen scalars. Nine scalars to store a transformation matrix, three scalars for position and three for storing its extent. An 18-dop is represented with eighteen scalars to represent the volume extent in each one of the nine directions. OBBs and 18-dops require 2.5 and 3 times more storage than AABBs, respectively.

In some applications it is also necessary to insert and delete 3D models interactively, without expending too much time re-computing the data structures. Van Der Bergen [1997] found that building an OBB tree takes three times more time than building an AABB tree. Furthermore, Van Der Bergen showed that updating an AABB tree as a model is deformed is significantly faster than in an OBB tree. Hence a bounding volume hierarchy of axis-aligned bounding boxes also offers the flexibility to develop an efficient collision detection algorithm for models that can deform with time.

3.2 Bounding Volume Update

In general, each one of the three-dimensional models of a scene graph is represented in its own local coordinate system and positioned in the world coordinate system using a transformation matrix. The bounding volume structure of an object that is created for improving the performance of the collision detection process is also defined in the object's local coordinate system. The geometry and the bounding volume structure of each object are defined in its own local coordinate system. For two objects *A* and *B*, two transformation matrices, $M_{wc \leftarrow A}$ and $M_{wc \leftarrow B}$, are defined that convert the local representation of the two objects into the world coordinate system.

When two objects are tested for intersection, the collision detection process first checks the bounding volumes for overlapping. However, for AABBs and *k*-dops, the bounding volumes of each object are aligned in different object's local coordinate systems. To test if two bounding volumes are overlapping, these volumes must be represented in the same coordinate system. The operation of transforming the bounding volumes to the same coordinate system, for performing the overlapping test, is called a *bounding volume update*.

Two cases can be considered in the choice of a common coordinate system for performing bounding box intersection. The bounding volumes of objects *A* and *B* can be updated into the world coordinate system, e.g. the $BV_A(A)$ and $BV_B(B)$ are transformed into $BV_{wc}(A)$ and $BV_{wc}(B)$; or the bounding volumes $BV_B(B)$ of object *B*, are updated into the coordinate system of object *A*, $BV_A(B)$. The second approach is better since it performs half of the bounding volume update operations. Furthermore, the second approach uses the original bounding volume of object *A*, which is tighter to the underlying geometry than an updated bounding volume.

S-CD updates the bounding volumes of object *B* into the coordinate system of object *A*.

The axis-aligned bounding volumes of object *B*, are originally aligned with its own local coordinate system. When the AABBs of object *B* are updated to the local coordinate of object *A*, they are not aligned with the coordinate system of object *A*. Therefore, a new AABB, which is aligned with the coordinate system of object *A*, needs to be computed for object *B*.

One approach for computing the new bounding box is to determine the *optimal* AABB of the transformed object within the coordinate system of object *A*, $AABB_A(B)$. This requires a brute force approach that will transform all the underlying geometric primitives of *B*, into the coordinate system of A, by applying a transformation matrix $M_{A \hookleftarrow B}$. The new $AABB_A(B)$ is then built by computing the new minimal and maximal values in the x, y and z axes, defining the new extents of the bounding volume. This approach has a major drawback. It takes too much time for interactivity for a large number of underlying primitives. However, the advantage of this approach is that the resulting bounding volume is an optimal AABB that better encloses the underlying geometries.

The second approach is to determine a *cover* $AABB_A(B)$, which is an approximation of the optimal axis-aligned bounding box of B that can be determined with the brute force approach. Initially, the eight vertices of the transformed AABB of object B are computed into the coordinate system of A. The extents of the cover AABB are determined by finding the minimal and maximal values of these transformed eight vertices. The cover AABB volume is greater than that of the brute force AABB approach, but is faster to compute.

In the implementation of S-CD, both approaches are used. The axis-aligned bounding boxes in the inner nodes of the bounding volume hierarchy are updated by determining a cover axis-aligned bounding box. For the leaf nodes of the bounding volume hierarchy, a new optimal axis-aligned bounding box for the transformed triangles is computed, since it is faster to do so. This optimal axis-aligned bounding box is found by transforming the triangle and computing a new AABB from the three vertices of the triangle. A cover AABB transforms the eight vertices of an AABB and computes a new bounding volume, taking more time.

3.3 R-Tree for the Collision Detection Problem

It was decided to use R-trees [Guttman 1984] to build the bounding volume hierarchies and organize the 3D geometry of objects for improving the performance of the collision detection process.

Some important properties of the R-tree can be underlined here that contributed to its choice: 1) At any level of the tree, each primitive is associated with only a single node; 2) In an R-tree all leaf nodes appear on the same level; 3) The depth of a R-tree storing n primitives is $\log_m n$, m is the minimum number of children of a node; 4) The total number of primitives stored in a R-tree equals the number of original primitives.

For the implementation of the collision detection algorithm each object is represented by an R-tree data structure in its own local coordinate system (Figure 1-a). A hierarchical tree is built, grouping neighboring surfaces. The leaf nodes of the R-tree point to the geometry of the surfaces that define the object. For two objects, it checks for collisions between surfaces which are in the neighborhood, eliminating comparisons with those which are far away.

The same idea is applied for surfaces. Surfaces from a three-dimensional model can be complex with a large number of triangles. An R-tree can be used to organize the triangles spatially and hence to quickly reject triangles that cannot intersect (Figure 1-b). In this approach, an R-tree is computed for each surface, grouping neighboring triangles to eliminate comparisons with those that are faraway from the area of intersection.

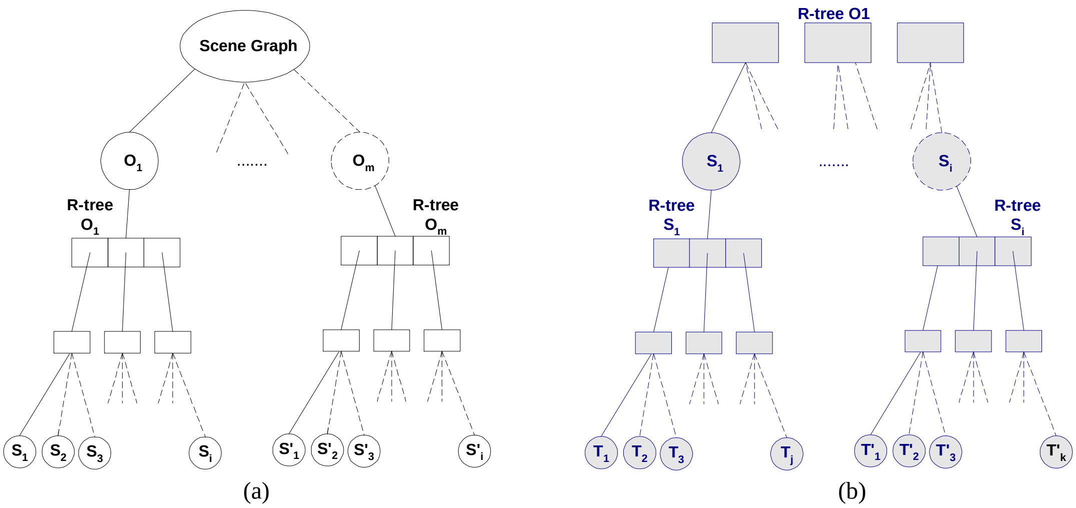


Figure 1. (a) Each object of the scene graph is represented by its own R-tree data structure representing its surfaces. (b) Each surface of the 3D model is also represented by its own R-tree data structure.

3.4 Overlapping Axis-Aligned Bounding Box

The proposed algorithm is based in the use of the *Overlapping Axis-Aligned Bounding Box*, *OAABB*(*A*, *B*), of two geometric primitives, to improve the performance of the collision detection process. Figueiredo et al [1993] introduced this concept for improving performance in the determination of intersecting polygons. Smith et al [1995] also use the same concept together with an octree data structure for finding intersecting polygons. S-TCD extends the OAABB concept for surfaces.

The OAABB is defined as the volume that is common to two axis-aligned bounding boxes of *A* and *B*, *AABB(A)* and *AABB(B)*, aligned with the coordinate axes.

The OAABB is used to filter out primitives that cannot intersect. Consider the 2D example of Figure 2. For two polygons in 2D, the collision detection process wants to determine intersecting edges. Axis-aligned bounding volumes for each edge are used to filter out pairs of edges that cannot intersect.

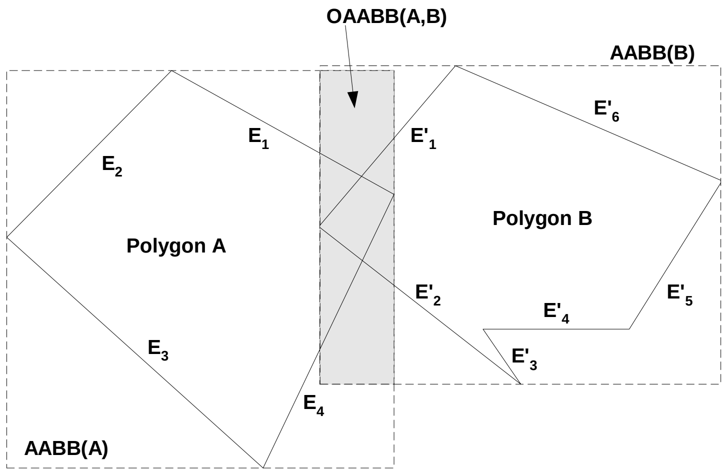


Figure 2. The Overlapping Axis-Aligned Bounding Box (OAABB) concept shown in 2D.

Two edges, E_i and $E_j^{'}$ from polygon *A* and *B* respectively, intersect if they also intersect the overlapping axis-aligned bounding box of the two polygons. In this way, edges whose AABB do not intersect the *OAABB(A,B)* are filtered out. Therefore, the first step of a collision detection algorithm based in the OAABB concept is to test every edge of *A* and *B* against the overlapping bounding volume. The candidate edges that overlap OAABB are passed to the next stage of the collision detection pipeline.

This approach is more effective in those environments where most of the intersections are superficial and the OAABB is small compared to objects. If the AABB of one of the objects is about the same size of the OAABB, this approach does not filter out many edges.

The use of the overlapping bounding volume also reduces the number of bounding volume update operations.

Initially, the overlapping bounding volume is defined in the coordinate system of *A*. To determine the edges of *A* that intersect the OAABB, it is not necessary to execute any update operation. To determine the edges of *B* that intersect the OAABB only one update operation is required, independent of the number of primitives of *B*. The OAABB, defined in the coordinate system of *A*, is transformed into the coordinate system of *B*.

4. S-CD TOOLKIT IMPLEMENTATION

This section presents the algorithm for determining intersecting surfaces between a pair of 3D objects. This paper presents the latest development of some of the initial ideas presented earlier in [Figueiredo and Fernando 2003] and [Figueiredo and Fernando 2004] and it is the result of the gathered experience obtained with real industrial case studies. It also describes a novel implementation of the traversal algorithm for collision detection that takes advantage of the R-Trees structure.

The algorithm to find intersecting surfaces is presented in Figure 3.

The collision detection algorithm, described in the following paragraphs, takes advantage of the scene graph structure built from 3D data models. In this approach, each 3D model is defined as a collection of surfaces. Each surface is tessellated individually and represented as a collection of triangles.

The collision detection process first checks if objects *A* and *B* are disjoint (line 1-2 in Figure 3). The bounding volumes of each object are originally computed in the object's local coordinate system, $AABB_A(A)$ and $AABB_B(B)$, respectively. The transformation matrix that converts the local representation of object *A* into the local coordinate system of object *B* is defined as $M_{B\leftarrow A}$. The bounding volume of object *A* is updated to the coordinate system of object *B*, by computing the cover axis-aligned bounding box, $AABB_B(A)$. Once the bounding volumes of each object are in the same coordinate system they can be checked for overlap. If this pair of AABBs does not overlap, then the corresponding two objects are not intersecting and the process ends. If they overlap, then the system determines the Overlapping Axis-Aligned Bounding Box, $OAABB_B(A,B)$ of the two objects (line 3 in Figure 3), which is defined in the local coordinate system of object *B*.

```
S-CD_Collide (A, B)
1:AABB_B(A)=M_B←A·AABB_A(A)//update Cover BV
2:if (AABB_B(A) do not intersect AABB_B(B))     return
3:Determine OAABB_B(A, B)
4:DescendRtree(SBV(B), OAABB_B(A,B))
5:for each surface from SBV(B) intersecting OAABB_B(A,B)
6: DescendRtree(TBV(B), OAABB_B(A,B))
7: for each triangle T(B) from TBV(B) intersecting OAABB_B(A,B)
8:  Update triangle T(B) geometry into coord. system of A
9:  Compute the new optimal AABB_A(T(B)) for T(B)
10: DescendRtree(SBV(A), OAABB_A(A,B), AABB_A(T(B)))
11: for each surface from SBV(A)
12:  DescendRtree(TBV(A), AABB_A(T(B)))
13:        Intersect T(A) and T(B)
```

Figure 3. Pseudo-code for finding intersecting surfaces.

The next step of the collision detection process determines the surfaces from object *B* intersecting the OAABB (line 4 of Figure 3). As mentioned before, the surfaces of object *B* are organized in a Surface Bounding Volume R-tree called *SBV(B)*. The surfaces of *B* are stored at the leaf nodes of the *SBV(B)* R-tree. By descending this R-tree, the surfaces of object *B* that do not intersect the $OAABB_B(A,B)$ are filtered out. Only the surfaces at the leaf nodes intesecting the $OAABB_B(A,B)$ are candidate for collision.

Each surface of object *B* is tessellated and represented by a collection of triangles. The triangles of each surfaces are also represented in its own Triangle Bounding Volume R-tree data structure, organizing its triangles into sub-regions. The next step of the collision detection process descends to the Triangle Bounding Volume R-tree *TBV(B)* of each candidate surface from object *B* (lines 5 and 6 of Figure 3). This stage determines the triangles of object *B* intersecting the OAABB.

Using the OAABB, the collision detection manager filters out surfaces and triangles of object *B* that cannot intersect.

The triangles of object *B* intersecting the OAABB are transformed into the coordinate system of object *A* (line 8). At this point is also determined the triangle's optimal bounding volume (line 9). The new optimal AABB is built by computing the new minimal and maximal values in the *x*, *y* and *z* axes, defining the new extents of the bounding volume. This stage computes the optimal bounding volume, since it is faster than computing the cover AABB. Furthermore, the optimal AABB encloses the triangle better than a cover AABB.

Then, the collision detection process descends the Surface Bounding Volume *SBV(A)* R-tree for object *A* (line 10 of Figure 3). In this step it finds surfaces of object *A* intersecting the OAABB and the triangle's optimal $AABB_A(T(B))$ of object B.

To determine if a pair of surfaces intersects, it is necessary to find a pair of intersecting triangles. Then, the collision detection process descends to the Triangle Bounding Volume R-tree *TBV(A)* of each candidate surface from object A (lines 11 and 12 of Figure 3). This stage determines the triangles of object *A* who's bounding volumes intersect the triangle's optimal AABB of object B.

The final step is to proceed with the intersection between pairs of candidate triangles (line 13) implemented with Guige and Devillers [2003] algorithm. If there is a pair of intersecting triangles then the corresponding surfaces is intersecting.

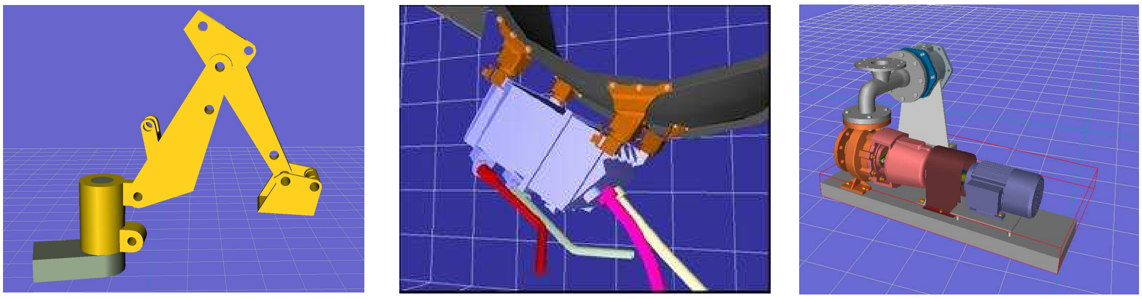
5. EXPERIMENTAL RESULTS

This section presents the performance evaluation results of the novel collision detection algorithm described in this paper.

Three examples that represent user operations to assembly the components of the described models are used. Case study 1 (Figure 4-a) is the assembly process to build a digger mechanism from D-cubed Ltd. Case study 2 (Figure 4-b), from the Sener Company in Spain, is the building process of an electronic control box from an aircraft engine. Case study 3 (Figure 4-c), from UMIST in Manchester, is the assembly of a process plant. These test scenarios are real case applications from maintenance simulation in virtual prototyping environments. For example, case study 2 from SENER Company in Spain, is part of a real product development from the aerospace domain, where SENER was responsible for designing connectors, tubing, wire harnesses, brackets, clips, and accessories for an aircraft engine electronic control box. It reflects the real scenario and the working environment, including the complexity of the model and the realism of the activities. The real working requirement on which the test case is based on was to demonstrate to the customer that the electronic control box from an aircraft engine can be removed and replaced from the airframe in less than 60 minutes following the instructions defined in the standard maintenance handbook.

Table 1 shows the complexity of the digger, sener and process plant environments. The most complex case scenario, in terms of number of objects in the scene, is the sener model with 25 objects (parts). The sener and process plant have about the same complexity when related to the number of surfaces and the total number of triangles in the scene. The process plant has a lower number of objects in the scene than the sener model. The digger model has a lower number of surfaces and triangles. Table 1 also presents the total number of intersecting steps for the assembly operations for each case study.

All the experiments run in an Intel Core 2 Duo T7300, 2GByte of RAM memory at 2GHz.



(a) (b) (c)

Figure 4. Test case scenarios: (a) Digger model; (b) Sener Model and (c) Process plant.

Table 1. Complexity of the models used in test case scenarios

Test Case Scenario	*Digger*	*Sener*	*Process Plant*
Number of Objects	5	25	8
Total Number Surfaces Scenario	109	1 250	1 073
Total Number Triangles Scenario	2 452	25 525	24 415
Number of intersecting steps for the entire assembly simulation	507	980	233

The collision detection implementation can be configured to determine first intersecting surface, all intersecting surfaces or all the intersecting triangles between three-dimensional components in a virtual prototyping environment. Table 2 presents these times. The proposed collision detection algorithm achieves interactive rates in real industrial applications as desired.

It is also important to compare the performance of this algorithm with other collision detection toolkits. Tables 3 and 4 present the times obtained comparing the implementation described in this paper, named as S--CD (Surface Collision Detection), with PQP, RAPID, OPCODE and Dop Tree. The times presented were obtained in the determination of the first intersecting triangle (Table 3) and also for all the intersecting triangles (Table 4). S-CD is effective in the determination of intersections interactively.

Table 5 presents the time obtained when the overlapping axis-aligned bounding box (OAABB) approach is not used. This table presents the time to find first, all intersecting surfaces and all intersecting triangles.

Tables 2 and 5 show there is an improvement in performance by using the overlapping axis aligned bounding box.

This improvement is explained by table 6. The cost of finding collisions depends on several factors. The choice of type of bounding volume influences the number and the cost of executing bounding volume intersections. For AABBs and *k*-dops the cost and the number of updating bounding volumes also influences performance. Table 6 shows an effective reduction in the number of AABBs tests and update bounding volume operations explaining the better performance obtained by the OAABBs.

Table 2. Collision detection time to find intersecting surfaces

Time in milliseconds per step to determine:	*Digger*	*Sener*	*Process Plant*
(i) first intersecting surface per step	0.04	0.15	0.09
(ii) all intersecting surfaces	0.25	0.55	0.94
(iii) all intersecting surfaces and all intersecting triangles	0.36	0.72	1.26

Table 3. Time to find first triangle intersection

Time to find first triangle intersection (milliseconds)	*Digger*	*Sener*	*Process Plant*
PQP	0.42	0.32	0.40
RAPID	0.06	0.10	0.12
OPCODE	0.02	0.08	0.04
Dop Tree	0.77	1.25	1.52
S-CD	0.04	0.15	0.09

Table 4. Time to find all triangle intersections

Time to find all triangle intersections (milliseconds)	*Digger*	*Sener*	*Process Plant*
PQP	1.82	1.57	4.96
RAPID	1.24	1.18	3.62
Dop Tree	5.81	10.48	17.29
OPCODE	0.90	1.73	2.09
S-CD	0.36	0.72	1.26

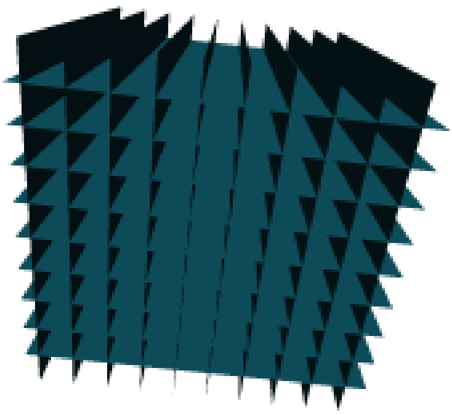
Table 5. Collision detection time to find intersecting surfaces (without using OAABB)

Time in milliseconds per step to determine:	*Digger*	*Sener*	*Process Plant*
(i) first intersecting surface per step	0.09	0.38	0.28
(ii) all intersecting surfaces	0.34	1.06	1.75
(iii) all intersecting surfaces and all intersecting triangles	0.50	1.23	2.06

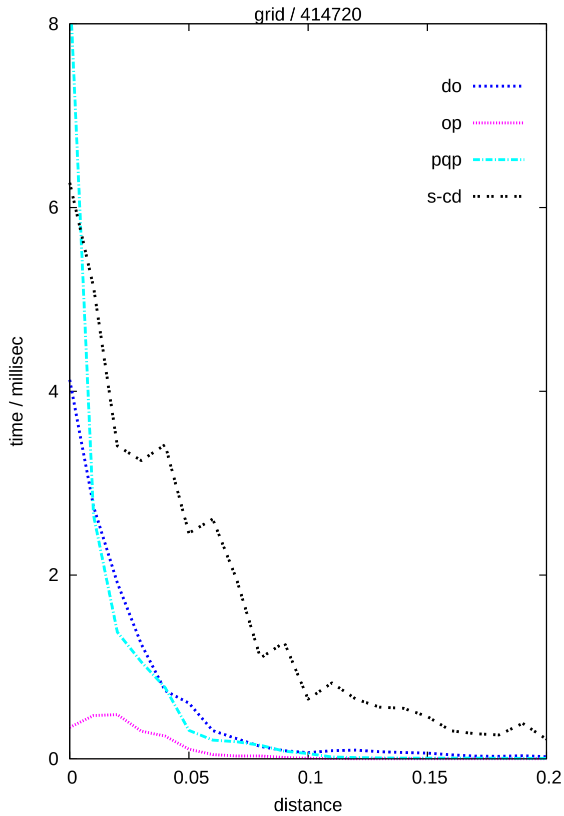
Table 6. Average number of operations per step to determine first intersecting surface

Number of operations:	*Digger*		*Sener*		*Process Plant*	
Using OAABB	Yes	No	Yes	No	Yes	No
AABBs tests	507	754	2256	3942	1263	2915
AABBs updates	39	202	87	825	102	713

Next, S-CD and other collision detection toolkits are evaluated using a benchmarking suite [Trenkel et al 2007] to compare pairwise static collision detection algorithms for rigid objects. This benchmark generates a number of positions and orientations for a predefined distance in close proximity. It does not test performance of collision detection approaches when intersections occur. Figure 5 shows that S-CD runs interactively as desired. It should be regarded that in this benchmark S-CD does not uses surface knowledge and in this way S-CD does not use all its features to improve performance.



(a)



(b)

Figure 5. (a) The grid scene with 414 720 faces. (b) Results of the benchmark. The x-axis denotes the relative distance between the objects, where 1.0 is the size of the object. Distance 0.0 means that the objects are almost touching but do not collide. The abbreviations for the libraries are as follows: do=Dop-Tree, pqp=PQP, op=Opcode, s-cd=S-CD.

6. CONCLUSION

This paper presents a novel collision detection algorithm for supporting assembly and maintenance simulations in virtual prototyping environments which is publicly available at http://w3.ualg.pt/~mfiguei. It determines intersecting surfaces between three dimensional components at interactive rates.

To improve performance, the collision detection uses the overlapping axis-aligned bounding box approach (OAABB), axis-aligned bounding boxes (AABBs) and the R-tree structure. The OAABB approach is used effectively together with the two level hierarchy of R-tree structure to reduce the number of updates and checks between bounding volumes, taking the effective advantage of the low cost of intersecting AABBs. It is also described a novel traversal algorithm that takes effective advantage of the two-level R-tree structure. The use of OAABBs also allows the significant reduction of the number of bounding volume intersections and updates.

The approach presented in this paper was tested with industrial maintenance scenarios of moderate complexity that were used to test assembly operations, running in an Intel Core 2 Duo T7300 at 2GHz. The proposed approach determines intersecting surfaces interactively and effectively addressed the assembly operations carried on.

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