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AN APPROACH TO CONTACT DETECTION IN VR-SIMULATIONS*

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Abstract. *Virtual Reality (VR), as a novel technology that allows the user to interact with an artificial environment, is a demanding multi-disciplinary field. It requires very efficient physics-based computations yielding reasonable accuracy, with plausible physical behavior being the minimum requirement. A simplified co-rotational FEM formulation, which accounts for large local rotations on element level, is used as a basis for computing deformational behavior in this paper. Real-time detection and realization of contact between deformable objects is a challenging task. The paper presents an approach to efficient contact detection between deformable objects, the geometry of which is described by triangulated surfaces, for the purpose of VR-simulation.*

Key words: *Virtual Reality, Contact Detection, Geometrically Nonlinear FEM*

1. INTRODUCTION

Simulations in the field of Virtual Reality (VR) require a multidisciplinary approach that combines mechanics, numerical computation, computer graphics – to name but a few. The background of VR-simulations is an artificial, computer generated environment often comprising dynamically deforming objects, which can be interacted with. The quality of animation and rendering is very important for VR-applications, since it determines the very first impression of achieved results. However, it is the displayed physical behavior of the objects that eventually determines the simulation quality, i.e. the degree of realism exhibited by the simulated environment.

In many areas of application, VR requires simulation of deformable objects' behavior involving large deformations. An example of such a requirement is found in some special applications of VR technology, such as various surgical simulators, especially those in-

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volving soft tissues. While typical engineering computations are done "off-line" and set accuracy as the primary objective, it is the computational efficiency and stability that get priority in the field of VR. Of course, the plausibility of deformational behavior, as a minimum requirement, has to be fulfilled. Therefore, for the purpose of computation of deformational behavior, the authors use the recently developed and rather efficient co-rotational geometrically nonlinear FEM formulation, which accounts for large local rotations on element level [3]. The essence of this formulation will be briefly described in the paper.

Another important request for VR applications is collision detection. A highly efficient approach to collision detection and, furthermore, contact realization that would be applicable in real-time simulations, i.e. at interactive frame rates, is still a challenging task. In the last couple of decades, many researchers have addressed the problem in their work (e.g. [1, 2, 4, 5]). This paper presents the authors' initial development to address the problem of contact detection. Though the development has been done keeping the request for high efficiency in mind, it is the functionality that is set as a primary objective in the very first step. This implies that the approach to be presented in the paper is expected to undergo further improvements.

2. Simplified Co-Rotational Geometrically Nonlinear FEM Formulation

A geometrically nonlinear co-rotational FEM formulation implies that the geometrical nonlinearities in structural behavior are accounted for by means of an auxiliary, local reference frame that is attached to the material and performs the same rigid-body motion as the structural material. Such an approach decouples rigid-body motion from deformational motion, thus allowing usage of engineering strain and stress measures in the formulation and, furthermore, decoupling geometrical from material nonlinearities. Theoretically, a co-rotational reference frame may be assigned to each material particle. In FEM formulations, this is typically done for each element integration point as those points are used in the evaluation of element tangential stiffness matrix. However, in the simplified co-rotational formulation, the essence of which is presented in this section, the rigid-body rotation is accounted for on a somewhat rougher level. Actually, an average rigid-body rotation is determined for each finite element and further used in the computation.

Compared to rigorous geometrically nonlinear formulation, the essence of the present formulation consists in implemented simplifications for the computation of internal elastic forces and structural tangential stiffness matrix. The idea of the formulation is to keep purely linear elastic behavior of single elements with respect to the local reference frame. The computed averaged rigid-body rotation of an element is used to determine rotation-free displacements, rotate internal forces from initial to current element configuration and rotate the element stiffness matrices. More details about the formulation are available in [3]. The core equation of the formulation gives the internal element forces in the current element configuration:

$$\{F_e\} = [R_e]\ [K_e]\ \left([R_e]^{-1}\{u_e\} - \{u_{0e}\}\right). \qquad (1)$$

where $\{u_{0e}\}$ and $\{u_e\}$ are the initial and current element configurations (nodal coordinates), respectively, $[K_e]$ is the element linear stiffness matrix and $[R_e]$ is the transformation matrix describing the element rigid-body rotation.

Hence, the formulation allows computation of single element stiffness matrices in a step prior to interactive simulation. Over the course of simulation, it is necessary to determine the rotational matrix of each single element, rotate the element stiffness matrices, re-assemble the structural stiffness matrix, determine internal forces and solve the system of equations. The developed formulation is used in combination with a pre-conditioned conjugated gradient (iterative) solver that takes advantage of the structural matrix in the sparse form and the possibility of performing a trade-off between the accuracy and numerical efficiency by limiting the number of performed iterations.

3. CONTACT DETECTION APPROACH

Having given the fundamental idea of the FEM-formulation used for computation of deformational behavior, the focus is now upon the formulation of an algorithm for contact detection between deformable objects. The term 'contact detection' refers here to the computational problem of determining the intersection of two or more objects. An additional problem is the fact that the considered objects are not rigid bodies, but deformable and can undergo large deformations, which implies significant changes in their geometry. Hence, a robust approach to contact detection that is completely independent of current objects' geometry is required. It is assumed that the complex geometry of deformable objects is represented by surface vertices interconnected into triangular faces (triangulated surface).

3.1. Axis-aligned boundary boxes

The first step in the proposed algorithm has the objective of efficient narrowing the set of surface vertices and faces which might be colliding and eliminating those object pairs which are of no immediate interest from the point of collision detection. This is done by means of bounding volumes, which may be of different shapes, such as spherical, rectangular, elliptical, etc. Due to its simplicity and suitability in application, axis-aligned boundary boxes (AABB) are applied in this work. For each deformable body, an AABB is determined as a current boundary box (cuboid) aligned with the axes of the global coordinate system. The AABB is represented by six numbers, typically the coordinates of the two vertices having the minimum and maximum values of all vertices representing the geometry of a deformable object:

$$\begin{aligned} &x_{\min} = \min(x_i), \quad y_{\min} = \min(y_i), \quad z_{\min} = \min(z_i) \\ &x_{\max} = \max(x_i), \quad y_{\max} = \max(y_i), \quad z_{\max} = \max(z_i) \\ &i = 1,\ 2,\ \ldots,\ N_n \end{aligned} \tag{2}$$

with N_n denoting the number of vertices representing the geometry of a deformable object. The total number of steps for determining an AABB for a deformable object linearly depends on the number of object's vertices, N_n, i.e. n = O (N_n). Fig. 1 depicts the same object variously oriented with respect to the global coordinate system and the corresponding AABBs.

An existing intersection of two AABBs indicates a possible collision between the associated objects. For each of the three global coordinates, the minimum coordinate of the intersection of two AABBs would be the greater value of the corresponding minimum coordinates of each AABB. Similarly, the maximum coordinate for all three global directions would be the less value of the corresponding maximum coordinates of each AABB.

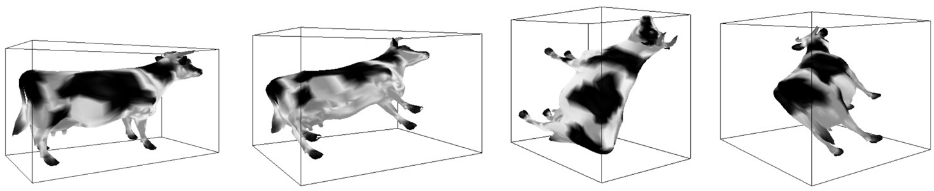

Fig. 1. Axis-aligned boundary boxes (AABBs) for a variously oriented object

The actual existence of the intersection is then determined by conjunction of the three conditions:

$$\begin{aligned}
&\bar{x}_{\min} = \max(x_{\min 1},\ x_{\min 2}), \quad \bar{x}_{\max} = \min(x_{\max 1},\ x_{\max 2}), \quad \bar{x}_{\min} < \bar{x}_{\max} \\
&\bar{y}_{\min} = \max(y_{\min 1},\ y_{\min 2}), \quad \bar{y}_{\max} = \min(y_{\max 1}, y_{\max 2}), \quad \bar{y}_{\min} < \bar{y}_{\max} \\
&\bar{z}_{\min} = \max(z_{\min 1},\ z_{\min 2}), \quad \bar{z}_{\max} = \min(z_{\max 1},\ z_{\max 2}), \quad \bar{z}_{\min} < \bar{z}_{\max}
\end{aligned} \tag{3}$$

where the values in the parenthesis are the maximum and minimum coordinates of the AABBs of the two considered objects. Hence, if an intersection of AABBs exists, then a further check on collision detection is required. At this point, a possible extension of the AABB application should be noted. The performance can be improved by using a hierarchical AABB structure, i.e. a tree of AABBs. When an intersection of the top level AABBs is detected, the same approach is applied onto the subparts of the deformable bodies positioned within the intersection. Such an example is given in Fig. 2, where two levels of AABBs are used. The figure also depicts the vertices, which are collision candidates, i.e. which are positioned in the lower level AABB. The approach with hierarchically structured AABBs may significantly reduce the set of vertices that are colliding candidates in the case of rather incoherent, complex geometries.

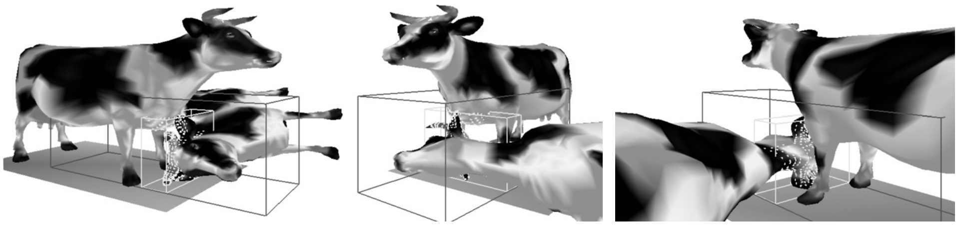

Fig. 2. Intersections of hierarchically structured AABBs and vertices which are collision candidates

3.2. Axis-oriented ray-trace approach for collision detection

By means of AABB approach, the set of vertices and associated faces that are collision candidates is notably reduced. This enables large computational savings compared to a brute-force method which would simply perform a contact check on each vertex of a deformable body against all faces of another deformable body. The art of reducing the set of possibly colliding vertices and faces is very important, because it is always followed by a relatively time-consuming brute-force method for a definitive check on collision detection.

Fig. 3 depicts a frame from an interactive simulation involving two deformable spheres. The depicted spheres are colliding. Fig 3a gives the surface representation of the spheres and the detected intersection of the associated AABBs. In Figs. 3b and 3c only the candidates for colliding faces, i.e. the faces with at least one of the belonging vertices currently positioned in the intersection of the AABBs, are given in surface representation, while Fig. 3b gives also the spheres' FEM model in wire representation.

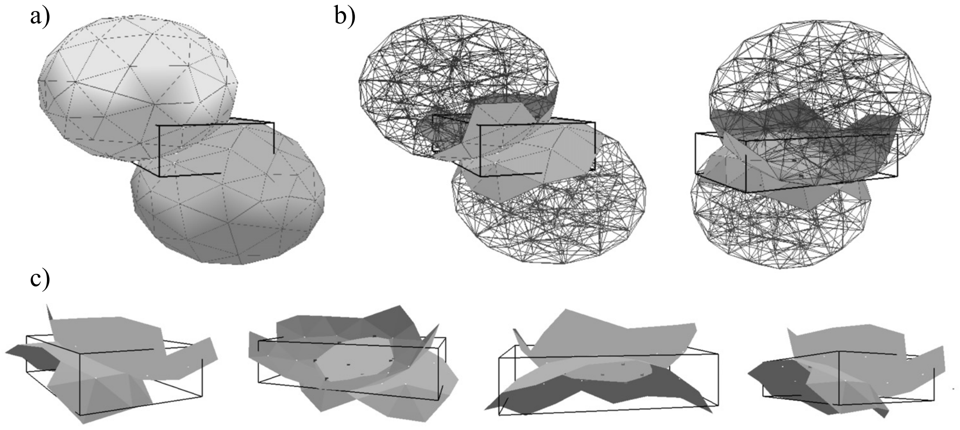

Fig. 3. Colliding deformable spheres with AABB intersection: a) surface representation, b) wire representation and collision candidate faces and c) only collision candidate faces

The definitive check on collision can be done in various ways. The final result of the check is the information if a vertex of a body is colliding with another body, or not. The authors use their own development for this purpose, which is denoted as axis-oriented ray-trace approach. Once a possible collision between two bodies is detected by means of AABBs and a set of possibly colliding vertices and associated faces is determined (as done in Fig. 3), the approach is applied for all vertices of a body positioned in the intersection of AABBs. The idea of the approach can be interpreted as if rays are started from a collision candidate vertex along the global axes and then it is observed if they intersect any of the faces of the other body within the intersection. Such a ray may intersect one or more faces of the other body within the intersection of AABBs. If intersections with more than one face are detected, then only the intersection with the closest face is of interest for further check on collision.

The actual realization of the idea is explained by means of Fig. 4. It is enough to explain the principle for a ray in one global direction, say x-direction. Exactly the same approach is applied for all three directions, if needed. At this point, it should be emphasized that the mentioned 'rays' are only a suitable way of visualizing the method. In the method's actual application, the projections of the collision candidate vertex of one body and collision candidate faces of the other body onto the corresponding planes are observed. For an x-direction 'ray' the corresponding plane would be the y-z plane (Fig. 4).

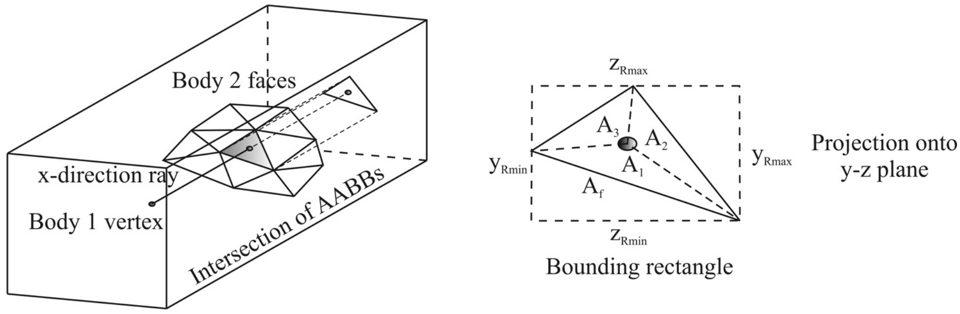

Fig. 4. Collision candidate vertex and faces; projection onto y-z plane

First, it is necessary to check if the projection of a vertex is inside the triangle that is obtained as a projection of a face. As already mentioned, this check implies a brute-force approach (within the intersection of AABBs all vertices checked against all faces). For that reason, it is necessary to have an efficient approach to promptly eliminate majority of the faces that would give a negative result on the aforementioned check, before a rigorous approach to perform the check is used. A similar idea to boundary boxes is applied here, but in this case, it is a boundary rectangle (Fig. 4). First, the minimum and maximum coordinates of the boundary rectangle of a face projection are determined in a way quite similar to Eq. (2), with *i* running only from 1 to 3 (the three vertices of the triangle) and only the *y*- and *z*-coordinates (for x-rays) are observed, thus yielding y_{Rmin}, y_{Rmax}, z_{Rmin} and z_{Rmax}. Hence, a necessary condition for a vertex projection (defined by y_v and z_v) to be within the triangle (face projection) is the conjunction of the following inequalities:

$$\begin{aligned} y_v > y_{R\,min}, \quad y_v < y_{R\,max} \\ z_v > z_{R\,min}, \quad z_v < z_{R\,max} \end{aligned} \tag{4}$$

The necessary condition is actually a very efficient way of eliminating a vast majority of faces that would yield a negative result on the rigorous check. If the necessary condition is met, then a rigorous check (sufficient condition) is performed. This is done by comparing surfaces of several triangles. Surface of face projection, A_f, is computed by means of *y*- and *z*-coordinates of the face vertices. The projection of the vertex forms a triangle with each edge of the face projection, so that three triangles are formed in this manner. The surfaces of those three triangles, A_1, A_2 and A_3 (Fig. 4), are also computed. Now, if the vertex projection is within the face projection, then the following condition is fulfilled:

$$A_1 + A_2 + A_3 = A_f\,, \tag{5}$$

or otherwise:

$$A_1 + A_2 + A_3 > A_f\,. \tag{6}$$

Eq. (5), or rather inequality (6) is used for the rigorous check. It might be very time-consuming to check each collision candidate vertex against each collision candidate face in this manner. This is why the efficient preliminary check by means of the necessary condition, given by inequalities (4), is important. It should be noted that a negative result on just one of the inequalities (4) suffices to cut further checks on the pair vertex-face and this would be the case with a vast majority of faces.

Finally, if the rigorous check has confirmed that the vertex projection was inside the face projection, it is necessary to determine if the collision candidate vertex is actually colliding. In order to do that, it is necessary to know the orthogonal face vector, pointing outside the body against which the vertex is checked on collision. The scalar product of the ray direction vector (the ray may run along positive or negative axis direction) with the orthogonal face vector gives the definitive answer on collision. If the scalar product is positive, then the vertex is colliding and vice versa. It should be noted that if the check with a ray in one direction has yielded a definitive result on collision, regardless if positive or negative, no further checks with rays in other directions are needed. If a definitive result is not obtained, then checks with rays in other directions are necessary until a definitive result is obtained or all three directions have been checked without a definitive result (which implies a negative result).

4. CONCLUSIONS

Virtual reality gains in importance in many areas of application. As a demanding multidisciplinary field, it requires efficient innovative approaches to provide real-time or nearly real-time solutions. The briefly mentioned co-rotational FEM-formulation is one of such approaches. Contact is another very important aspect of VR simulations. This paper describes an approach to contact detection. The approach is developed for triangulated surfaces but is easily extendable to another type of surface representation. It is important to notice that the approach is developed to detect contact based on actual objects' geometry. Namely, in many VR simulations involving deformable body behavior computed by means of FEM, the actual FEM models do not have to necessarily reflect the actual geometry. The FEM models can be set so as to yield a rough resemblance of the actual geometry and, in that case, coupled-mesh techniques are used to determine the deformed actual objects' geometry after the deformation has been computed based on such a rough FEM model. The fact that the contact is determined using the actual complex geometry provides better plausibility of simulation.

Contact detection is only the first step in resolving the contact issue. Contact handling, which implies computation of deformable bodies' reaction to contact, is the next important step. This is a work under progress and will be presented in future publications. It is also expected to improve certain aspects of the presented approach to contact detection.

REFERENCES

1. Duriez, C., Andriot, C., Kheddar, A., 2004, *Signorini's contact model for deformable objects in haptic simulations*, Proceedings of International Conference on Intelligent Robots and Systems, Sendai, Japan
2. Keiser, R., Mueller, M., Heidelberger, B., Teschner, M., Gross, M., 2004, *Contact Handling for Deformable Point-Based Objects*, Proceedings of Vision, Modeling, Visualization VMV'04, Stanford, USA, pp. 315-322

3. Marinković, D., Zehn, M., 2009, *FE-formulations for real-time simulations of large deformations*, Proceedings of NAFEMS World Congress, Crete, Greece
4. Ming, C. L., 1993, *Efficient collision detection for animation and robotics*, Ph. D. Dissertation, University of California, Berkley
5. Zhuang, Y., Canny, J.,1999, *Real-time simulation of physically realistic global deformation*, Proceedings of IEEE Visualization: Late Breaking Hot Topics, San Francisco, USA.

METODA ZA DETEKCIJU KONTAKTA U OKVIRU SIMULACIJA VIRTUELNE STVARNOSTI

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Virtuelna stvarnost, kao nova tehnologija koja omogućuje korisniku interakciju sa veštačkim okruženjem, predstavlja zahtevno multidisciplinarno polje rada. Ona zahteva veoma efikasne proračune bazirane na fizičkim zakonitostima koji daju zadovoljavajuću tačnost, pri čemu je uverljivo fizičko ponašanje minimum zahteva. Pojednostavljena korotaciona FEM-formulacija, koja uzima u obzir velike lokalne rotacije pojedinih elemenata, je korišćena u ovom radu kao osnova za proračun deformacionog ponašanja. Detekcija i realizacija kontakta između deformabilnih tela u realnom vremenu je izazovan zadatak. Rad predstavlja metodu za efikasnu detekciju kontakta između deformabilnih tela čija je geometrija predstavljena triangularizovanim površinama, a za potrebe simulacija virtuelne stvarnosti.

Ključne reči: *virtuelna stvarnost, prepoznavanje kontakta, geometrijski nelinearna FEM*