III INTERNATIONAL CONGRESS ON COMPUTATIONAL BIOENGINEERING
M. Cerrolaza, H. Rodrigues, M. Doblaré, J. Ambrosio, M. Viceconti
(Eds.)
Isla de Margarita, Venezuela, September 17 to 19, 2007

# APPLICATION OF A RESPONSE SCHEME FOR COLLISION HANDLING AMONG DEFORMABLE OBJECTS

**Bricelis J. Urbina*, Omaira Rodríguez**, Ernesto Coto*****

Computer Graphics Lab, Central University of Venezuela, Venezuela
* e-mail: bricelis@opalo.ciens.ucv.ve
** e-mail: omaira@opalo.ciens.ucv.ve
*** e-mail: ecoto@opalo.ciens.ucv.ve

**Keywords**: Deformable Models, Collision Handling, Laparoscopy Simulation, Virtual Reality.

**Abstract**. *Collision response schemes and deformable models have been recently an important subject of research, since many medical and entertainment applications require the simulation of real environments with deformable objects. Early research in this area comes from the field of Engineering, which propose very exact models but at a very high computational cost. New models propose plausible techniques which study the discrete nature of object representations in order to reduce the time required by these simulations. This paper presents the implementation of a very efficient collision response scheme which calculates the depth and direction of the penetration in the contact region, as well as the deformable model applied to the surface of the object. Furthermore, we present the application of the new collision detection scheme for the simulation of the interaction between a human abdominal organ and a surgery instrument.*

## 1 INTRODUCTION

In the last few years, the research community has accomplished significant advances in the area of medicine as well as in the techniques used in surgical procedures. Therefore, surgeons are frequently required to learn these new techniques in a short period of time and in the most possible efficient way.

For many years, virtual reality has been used successfully to simulate real environments for medical training. Surgical simulators allow the surgeon to develop and to acquire the skills required by these procedures through frequent practice, increasing their experience as well as the safety of their patients.

Following these research trend, the Computer Graphics Laboratory (LCG) of the Central University of Venezuela has been developing project LAPAROS [1] over the last few years, which consists on a system for surgical training that allows the surgeon to develop and improve their abilities for laparoscopy. This system is based on virtual reality technology and three-dimensional computer graphics techniques which simulate the interaction between rigid objects, and provides the surgeons with a series of five exercises which improve their spatial location and coordination.

However, the greater challenge of this project is simulating surgical procedures which assist the surgeons in practicing the techniques applied in these procedures. Therefore, it is necessary to develop three-dimensional models corresponding to the abdominal organs of the human body and to apply a deformation model which allows the simulation of the appearance, properties and behaviors of these anatomical structures with surgical instruments.

## 2 RELATED WORK

Deformable models are a set of models and techniques which allow that curves, surfaces and volumes change their form according to the modification of parameters, applied forces, displacements of control points, restrictions and impenetrable obstacles [2]. Some of these models incorporate physic laws [2], which in the following are referred to as *physic models*. These models describe object deformations caused by applied forces under consideration of material properties and other environmental constraints. Physic models allow the simulation of mass-spring systems, flexible materials, human tissues, fabrics, etc. Early research in this area comes from the field of Engineering, which propose very exact models but at a very high computational cost [3]. However, new models propose plausible techniques which study the discrete nature of object representations in order to reduce the time required by these simulations [2, 4, 5]. This paper presents an implementation of a very efficient collision response scheme based on these new models and its application to the simulation of the interaction between a human abdominal organ and a surgery instrument.

## 3 SIMULATION OF SOFT TISSUES

The Computer Graphics Laboratory (LCG) of the Central University of Venezuela is provided with the visible male dataset [6], from which we segmented some of the abdominal organs of the human body. Following this, we generated the surface model of these anatomic structures using the method proposed in [7]. We also developed an efficient collision detection algorithm which uses an Axis Aligned Bounding Box (AABB) tree for each scene object so as to identify the colliding area between two objects. In addition, in order to visualize and configure the virtual scene, we implemented a scene tree which can be loaded and configured with instructions read from a text file.

Following this, we chose two efficient deformable models which allowed simulating the deformation of a human organ as it collides with a surgical instrument as well as the following restoration of the organ until it reaches its original form once the collision finishes.

The first deformable model was originally suggested by Heidelberger et al. [4]; it consists of a very efficient collision response scheme in the colliding area between two objects, where both objects consist of a series of tetrahedrons. The second deformable model was originally suggested by Teschner et al. [5]; it considers the conservative forces contained in the elastic materials when the system changes its initial state. In the following, we describe the implementation of a collision response scheme based on these two works.

### 3.1 Scheme of Response in the Colliding Region

Heidelberger et al. [4] proposes an algorithm which considers the forces in the colliding region of the object according to a penetration depth and direction in each colliding vertex of the deformable object formed by tetrahedrons. This algorithm originally consists of four stages, which we adapted to our needs and our input data. We joined the first and second stages of the original algorithm into the first stage of our algorithm. In addition, we adapted the fourth stage of the original algorithm to be applied over surface objects instead of tetrahedron volumes. In the following paragraphs, we briefly explain each stage of our algorithm:

**Stage 1:** This stage detects the collision between a rigid object and a deformable object, based of the AABB tree of each object. If two AABB nodes are intersected, we verify if any edge of the triangles in the AABB node of the deformable object is intersected with a triangle in the AABB node of the rigid object. If two triangles do intersect, we calculate and store the intersection point and the normal of the intersected triangle of the rigid object and identify colliding border vertexes and non-colliding border vertexes.

**Stage 2:** This stage is exactly the same as the third stage of the original algorithm. In this stage we calculate the penetration depth and direction for each colliding border vertex. The penetration depth uses the weighting function $\omega(x_i, p)$ described in Equation 1, where $x_i$ is the border colliding vertex and $\mathbf{p}$ corresponds to the intersection point. Equation 2 describes the penetration depth, where $n_i$ is the normal of the triangle intersected with the edge formed by $x_i$ and other non-colliding border vertex. The penetration direction $r(p)$ of each colliding border vertex is the normalized vector that results of Equation 3.

$$\omega(x_i, p) = \frac{1}{|x_i - p|^2} \tag{1}$$

$$d(p) = \frac{\sum_{i=1}^{k}(\omega(x_i, p) \,.\, (x_i - p) \,.\, n_i)}{\sum_{i=1}^{k} \omega(x_i, p)} \tag{2}$$

$$\hat{r}(p) = \frac{\sum_{i=1}^{k}(\omega(x_i, p) \,.\, n_i)}{\sum_{i=1}^{k} \omega(x_i, p)} \tag{3}$$

**Stage 3:** This stage corresponds to the fourth stage of the original algorithm. This stage originally consists on propagating the penetration depth and direction to the internal vertexes of the tetrahedral volume located inside of the rigid object. However, in our implementation the propagation is applied to the colliding vertexes in the surface of the object. These colliding vertexes are located inside of the rigid object. They are obtained by a heuristic that consists in verifying if a vertex is a colliding border vertex in the current step. If it does, then in the next step of collision verification the vertex will be a colliding vertex unless it is verified that it is a non-colliding border vertex. The penetration depth of these vertexes uses a weighting function $\mu(p_j, p)$ between each internal colliding vertex **p** and the processed colliding vertexes $p_j$ according to Equation 4. The penetration depth $d(p)$ is obtained in Equation 5, where $r(p_j)$ corresponds to the penetration direction of the processed colliding vertex $p_j$. The penetration direction $r(p)$ of each colliding vertex is the normalized vector that results of Equation 6.

$$\mu(p_j, p) = \frac{1}{|p_j - p|^2} \tag{4}$$

$$d(p) = \frac{\sum_{j=1}^{l}(\mu(p_j, p) \,.\, ((p_j - p) \,.\, r(p_j) + d(p_j)))}{\sum_{j=1}^{l} \mu(p_j, p)} \tag{5}$$

$$\hat{r}(p) = \frac{\sum_{j=1}^{l} \mu(p_j, p)\, r(p_j)}{\sum_{j=1}^{l} \mu(p_j, p)} \tag{6}$$

### 3.2 Deformable Model for the Non-Colliding Region

The deformable model presented in [5] considers forces derived by potential energies produced in each edge by the distance preservation, in each triangle by area preservation, and in each tetrahedron of the object by volume preservation. Equation 6 shows the distance preservation formula, where $p_i$ and $p_j$ correspond to the two vertexes of the edge. Equation 7 shows the area preservation formula, where $p_i$, $p_j$ and $p_k$ correspond to the three vertexes of the triangle. Equation 8 shows the volume preservation formula, where $p_i$, $p_j$, $p_k$ and $p_l$ correspond to the four vertexes of the tetrahedron.

$$E_D(p_i, p_j) = \frac{1}{2} k_D \left( \frac{|p_j - p_i| - D_0}{D_0} \right)^2 \tag{6}$$

$$E_A(p_i, p_j, p_k) = \frac{1}{2} k_A \left( \frac{\frac{1}{2}\ (p_j - p_i) \times (p_k - p_i)\ - A_0}{A_0} \right)^2 \tag{7}$$

$$E_V(p_i, p_j, p_k, p_l) = \frac{k_V}{2} \frac{\left(\frac{1}{6}(p_j - p_i) \cdot ((p_k - p_i) \times (p_l - p_i)) - V_0\right)^2}{V_0^2} \tag{8}$$

This model guaranties that the colliding region of the object will oscillate and it will come back to the initial form using a damping function. In addition, they propose that to deform a surface we can consider one tetrahedron for each triangle and each neighbor vertex connected to this triangle. We apply this model after the third stage of the algorithm applied to the colliding region.

## 4 TESTS AND RESULTS

We performed several tests to verify the correct operation and time performance of the implemented algorithms. These tests consisted in colliding two objects (one rigid and one deformable) with triangulated surfaces with three different resolutions: 241 vertexes and 480 triangles; 993 vertexes and 1984 triangles; and 4033 vertexes and 8064 triangles. A total of nine tests were performed, covering all possible combinations of the tested triangulated surfaces. Each test was initiated with a horizontal displacement of the rigid object, producing the collision with 40% of the deformable object area. Then, the rigid object was displaced vertically up and down, colliding with 20% of the deformable object area on each border. All tests were performed on a computer with 512 MB of memory and a 1.7 GHZ CPU. The following deformation approaches were evaluated:

- Response Scheme for Collision (RSC) in the colliding region.
- RSC + Deformable Model without restoration: It consists in applying the RSC in the colliding region and the propagation of forces to the rest of the non-colliding surface without restoring the modified vertexes.
- RSC + Deformable Model with restoration: It consists in applying the RSC in the colliding region and the propagation of forces to the rest of the non-colliding surface and then restoring the modified vertexes.

Table 1 shows the average time required for each collision step of the three deformation approaches applied. Figure 1 shows a graphical representation of these results for an easier comparison of the average times.

| | Resolution Rigid vs. Deformable | Response Scheme for Collision | RSC + Deformable Model without restoration | RSC + Deformable Model with restoration |
|---|---|---|---|---|
| Test 1 | 241x241 | 0,02219318 | 0,02886455 | 0,03093863 |
| Test 2 | 241x993 | 0,02643189 | 0,04148911 | 0,04729691 |
| Test 3 | 241x4033 | 0,042459626 | 0,10129949 | 0,11541373 |
| Test 4 | 993x241 | 0,025458446 | 0,03340169 | 0,03589672 |
| Test 5 | 993x993 | 0,030800238 | 0,05244825 | 0,05515859 |
| Test 6 | 993x4033 | 0,047078356 | 0,12458907 | 0,13218986 |
| Test 7 | 4033x241 | 0,037333984 | 0,05318061 | 0,0537442 |
| Test 8 | 4033x993 | 0,04425557 | 0,07724302 | 0,08916327 |
| Test 9 | 4033x4033 | 0,064828948 | 0,1787737 | 0,18106284 |

Table 1. Average times of nine tests of the three deformation approaches.

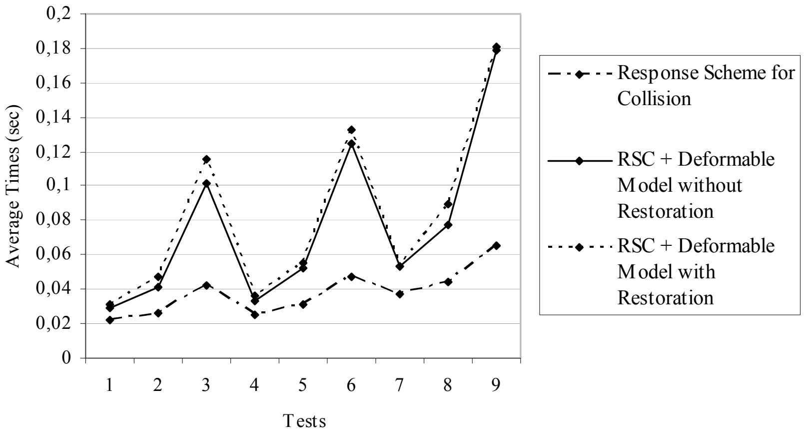

Figure 1: Comparison of average times of the three deformation approaches.

## 5 CONCLUSIONS AND FUTURE WORK

In general, average times are incremented when the resolution of the two objects is incremented. Likewise, the average times are higher when the resolution of the rigid object is less than the resolution of the deformable rigid.

Figure 1 shows that the response scheme to the collision is very fast since the average time of this algorithm was very low on each of the nine tests performed. Note that the averages times for the RSC with restoration and the RSC without restoration are slightly different. This indicates that most of the time consumed by these approaches is spent in the propagation of the non-colliding vertexes of the object rather than in the restoration of the colliding vertexes. Therefore, a further improvement to these approaches would be applying the propagation only to a certain number of non-colliding neighboring vertexes rather than to all the non-colliding vertexes of the object.

These algorithms can simulate the deformation produced in an abdominal human organ by the collision with a surgical instrument as well as the collision between elastic and plastic materials. In the LCG, we are working in the simulation of grasping and cutting to complete a surgery toolkit for the simulation of surgical procedures.

## 6 ACKNOWLEDGEMENTS

The work presented in this paper has been funded by the LAPAROS project, supported by the CDCH (Consejo de Desarrollo Científico y Humanístico) under the number PTP-08.12.5294.2004. We would like to thank Professor Rodolfo Miquilarena and Professor Miguel Cerrolaza for their invaluable contribution to this project.

## 7 REFERENCES

[1] B.J. Urbina, E.J. Coto, J.M. Motezuma, M. Martinez, M.E. Cerrolaza and O.C. Rodríguez, Measurement of the Improvement in Ability Laparoscopy using a Virtual Simulator, Proc. of CIMENICS'06, Margarita Island, Venezuela, 2006.

[2] E. Gladilin, Biomechanical Modeling of Soft Tissue and Facial Expressions for Craniofacial Surgery Planning, PhD Thesis, Freien Universität Berlin, Germany, 2003.

[3] D. Terzopoulous, J. Platt, A. Barr and K. Fleischer, Elastically Deformable Models, Proc. of The 14th Annual Conference on Computer Graphics and Interactive Techniques, ACM Press, New York, USA, pp. 205-214, 1987.

[4] B. Heidelberger, M. Teschner, R. Keiser, M. Müller and M. Gross, Consistent Penetration Depth Estimation for Collision Response, Proc. of Vision, Modeling, Visualization, ETH Zurich, Suiza, pp. 315-322, 2004.

[5] M. Teschner, B. Heidelberger, M. Müller and M. Gross, A Versatile and Robust Model for Geometrically Complex Deformable Solids, Proc. of Computer Graphics International, Crete, Greece, pp. 312-319, 2004.

[6] M.J. Ackerman, The Visible Human Project, Proc. of the IEEE, Vol. 86, No. 3, pp. 504-511, 1998.

[7] E. Coto and O. Rodríguez, T-Snakes and the Delaunay Triangulation for generation of anatomical structure meshes suitable for the Finite Element Method (In Spanish), Proc. of CIMENICS'04, pp. TC 11-18, 2004.