VOLUME OBJECT MODELING AND ANIMATION WITH PARTICLE-BASED SYSTEM

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ABSTRACT

In this article, we describe a general method for the reconstruction and animation of deformable 3D objects. These objects are initially defined by a closed surface model, which is filled with particles. For this, new particles are progressively generated inside the boundary. When a new particle is introduced, it enters in interaction with all the previously existing particles. It will also collide with the boundary. Then we let the system evolve under the action of physical laws until reaching an equilibrium. With an aim of a medical application, we want to simulate the movement and the deformation of anatomic objects. So we have introduced the necessary tools to take into account the dynamic and deformable behavior of the organs and the surrounding environment.

1. INTRODUCTION

Radiotherapy administers a lethal dose of ionizing radiation to the site of cancer cells with a minimum of damage to surrounding healthy tissue. The magnitudes of the radiation dose likely to be lethal to tumors are well known, as is the penetration of radiation into the human body. This knowledge has lead to the development of conformal radiotherapy. In this, the physician seeks to customize the radiation dose in both temporal and spatial terms to the specific requirements of each patient.

One of the major problems is a geometric problem concerning patient movement and alterations in shape and position. To solve this problem it is necessary to create geometrical models of the patient's body shape (external) and the treatment volumes (internal) and to correlate these two models in the same reference system.

In fact both the internal and external forms are dynamic and deformable, subject to internal and external forces, especially due to the natural rhythmic motion such as respiration. So we have to use models adapted to this kind of applications. One of the techniques that seems to be adequate is the physically-based particle model. Particle system are powerful techniques to model plastic, elastic, viscoelastic and fracture behaviors. In this model it is possible to introduce several kinds of geometrical constraints such as volume conservation to reproduce the behavior of cancerous tissues and organs.

The initial available data for the reconstruction of the desired forms is a closed surface, possibly described with implicit, polygonal or parametric models. In section 2, we present an original static volume reconstruction method based on particle system. In section 3, we introduce necessary tools for the simulation of the dynamic and deformable behavior of the organs. Some examples will illustrate the quality of the obtained results.

Related works

Many methods have been presented to handle deformations of 3D objects. In Neveu *et al.* (1995), a B-spline representation of a ventricle is deformed by displacing the control points. This permits to simulate the kinematics behavior of the organ. Superquadrics have been also used to model deformable surfaces, since they can be modified both locally and globally (Park *et al.*, 1994). The particle system is another interesting method. It has been introduced by Reeves (1983) to model fire and explosion of particles without interactions. Particle systems have been widely used since then. Szeliski and Tonnesen (1991) present a surface model with oriented particles, that permits to join, tear or extend surfaces. They also propose a way to reconstruct such surfaces.

Particle systems have also been used for deformable volumes modeling. Lombardo and Puech (1995) describe a method for modeling muscles with oriented particles and implicit surfaces. In the field of geometric reconstruction, lines, surfaces and volumes are successively filled with particles to obtain a 3D mesh, called "bubble-mesh" (Shimada and Gossard, 1995). Some works have been presented in the field of the reconstruction of deformable 3D objects. In Cotin *et al.* (1996), organs are reconstructed with tetrahedra, using a simplex-based meshing method. The result is used in a medical simulator.

Some authors have been interested in constrained deformations. An enumeration of the different constraints is

given as well as a method to solve them (Platt and Barr, 1988). Promayon *et al.* (1996) present a method to solve the difficult constraint of constant volume deformation for triangulated meshes.
However, all these works have been realized either in the scope of static reconstruction or animation. Few works make connection between reconstruction and animation. The originality of our work is to present a complete process, a reconstruction method that take into account the dynamic parameters of the object.

2. RECONSTRUCTION OF VOLUME OBJECTS

2.1 Description of the particle systems

A particle can be described by a mass, a radius, a position and a velocity vectors. Although they are very simple, particles are by far the easiest model to use. Moreover they are adapted to model complex behaviors, particularly deformable objects under constraints.
To simulate the displacement of the particles, Newtonian laws of physics are introduced. Forces could be of two kinds:

- internal forces which represent interaction between particles (short range attraction, long range repulsion);
- external forces, like gravity, collision or contact with obstacles.

The position of the particles can be determined by integrating the forces. For this we use a first order Euler's method:

$$v(d + dt) = v(t) + f(t)/mass * dt$$

$$p(t + dt) = p(t) + v(t) * dt$$

To raise the time step (and consequently reduce the number of iterations), it is possible to use greater order methods like Runge-Kutta integration.

2.2 Principle of the method

The initial data are closed surface boundaries described either by a set of facets or implicit surfaces. The reconstruction method consists in filling this object with particles to provide a regular or adaptive 3D sampling of the interior. This method allows to handle a great variety of shapes, comprising branches or holes.
To minimize the number of generated particles while respecting a precision criteria, we introduce the notion of layer (Fig. 1):

- a skin ensures the cohesion of the object. It is composed of small particles near the boundary to refine the model;
- a derm which permits the deformation, is composed of medium size particles;
- a nucleus composed by big particles in the center, where there is no need for a good precision.

The radius and the width of each layer determine the dynamic characteristics of the object. For example, the increase of the radius of the particles of the nucleus will reduce the capacity of the object to be deformed.

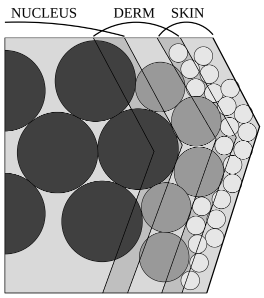


Figure 1: Layer structure

This methodology permits a maximal filling which is important to conserve the object's volume during the deformation.

2.3 Algorithm

The multi-layer reconstruction comprises different steps which are resumed in the following algorithm:

- Initialize the particles of the nucleus
- Repeat until precision criteria is reached:
  - new particles creation
  - computation of applied forces
  - determination of particles' positions by forces integration
  - if an equilibrium is reached, initialize particles of the next layer

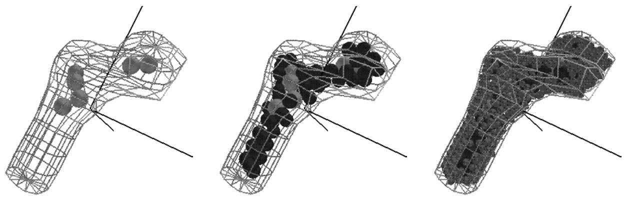
The figure (2) shows the evolution of the reconstruction of a 3D object defined by planar boundaries.

2.4 Applied forces

The forces applied to particles can be simply stated. To model the interaction between particles, we use the derivative force of the *Lennard-Jones* potential (Fig. 3):

$$E(r) = \frac{e}{m-n}\left[m\left(\frac{r_0}{r}\right)^n - n\left(\frac{r_0}{r}\right)^m\right]$$

$$\text{and } \vec{f}(r) = \overrightarrow{grad}\,(E(r))$$



(a) nucleus: 6 particles (b) derm: 39 particles (c) skin: 253 particles

Figure 2: Evolution of the reconstruction of a 3D object

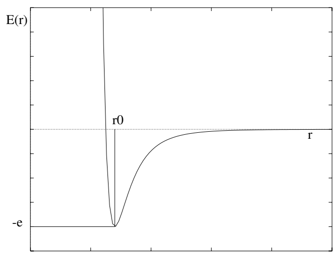


Figure 3: Lennard-Jones Potential

This force is divided into two parts: a short range repulsion ($r < r_0$) and a long range attraction ($r > r_0$). At $r = r_0$ the equilibrium state is reached.
We introduce collision forces to keep the particles inside the closed boundary. The collision response could be written as $\vec{v} = \vec{v}_t - r.\vec{v}_n$ where r is the restitution coefficient (Fig. 4).
If there is contact, the resulting force is $\vec{f}_c = -\left(\vec{n}.\vec{f}\right)\vec{f}$. This contact force lets the particle slip along the obstacle (Fig. 5). Some friction can easily be added: $\vec{f}_f = -k(-\vec{f}.\vec{n})\vec{v}_t$ acting tangentially to the contact plane.

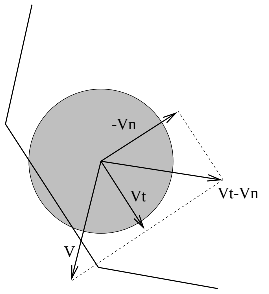


Figure 4: Collision response

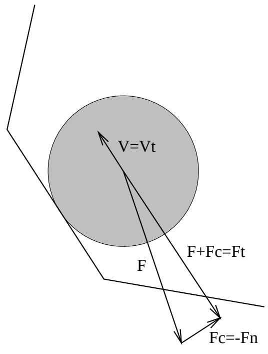


Figure 5: Contact response

2.5 Particle generation

The nucleus is modeled first by big particles far from the boundary. Next the mass and radius are decreased and the particles are allowed to come closer to the boundary to refine the object's shape. In 2D, the maximum filling mesh is hexagonal. Hence, symmetry or incomplete neighborhood can be used to generate new particles. Unfortunately, in 3D, this is not possible, particles can not be ordered. We must generate randomly candidate positions around existing particles, which act as seeds. Moreover, we have defined simple rules to determine if these positions are valid in order to create new particles. Thus, particles must be generated:

- in empty spaces, i.e.particles should not overlap;
- close to motionless particles;
- near the equilibrium position;
- in the range of the current layer to prevent the mixture of two consecutive layers.

3. DEFORMATION OF THE MODEL

In the previous section, we have defined a particle model that permits to handle easily the deformation of objects. The shape modification is induced by the collision with obstacles, which can be fixed or moving objects. The resulting displacement of the skin particles is propagated through the interior. Internal links between particles can be defined either with springs or spatial interaction forces.
After the reconstruction step, when the object is not "very deformable", the relationship between particles is modeled with springs. This reduces dramatically the complexity since the neighborhood of each particle is known and does not vary in time. However, this simplification imposes that there is no topological modification.
Unfortunately, springs tend to increase the rigidity of the object, and thus important deformations are not allowed. To solve this problem, a spring can be removed when its elongation is greater than a cohesion threshold. Then it is possible to simulate fracture.
To compute the force exerted by the particle #2 on #1, we write:

$$\vec{f}_{1\to 2} = -\left[k_s(r-l) + k_d\frac{\vec{v}.\vec{r}}{r}\right]\frac{\vec{r}}{r}$$

$$\text{and} \quad \vec{f}_{2\to 1} = -\vec{f}_{1\to 2}$$

where : k_s, stiffness $\quad \vec{r} = \overrightarrow{P_1P_2}$
k_d, damping $\quad \vec{v} = \vec{v_2} - \vec{v_1}$

Otherwise, when the object is considered as "very deformable", we must use spatial interaction (for example

Lennard-Jones potential). This permits to handle topological variation like break, hole formation ....

3.1 Different kinds of behavior

Different behaviors can be modeled by acting on the links between particles. For example, the parameters of the relationships between the particles determinate the elasticity and plasticity of an object. These parameters can be the stiffness and damping coefficient of a spring or the coefficients n and m of the Lennard-Jones potential function.
Moreover, we can easily model constant volume deformation, since the short range repulsion of the Lennard-Jones force prevents the particles to overlap. Then, the particles slip along each other and the volume defined by the set of particles remains approximatively the same during the deformation. This is particularly interesting since there is no need neither to compute the volume nor to solve a finite elements system (Promayon *and Al.*, 1996).
Anisotropic deformation can also be obtained (Fig. 6 left). The particles which compose the object have different parameters (light and dark colors on the figure), that could be the mass or the radius, or the coefficients of the interaction force.
Filling and emptying of a closed skin can easily be handled. For this, it is enough to add or remove particles inside the object. The skin can be modeled with oriented particles described by Szeliski and Tonnesen (1991). Hence some constraints can be added on the links to obtain a constant area deformation or an elastic behavior of the skin (Fig. 6 right). In case of filling, the new generated particles push the existing ones, deform the boundary and increase the volume. The added particles can also have parameters different from the existing particles.

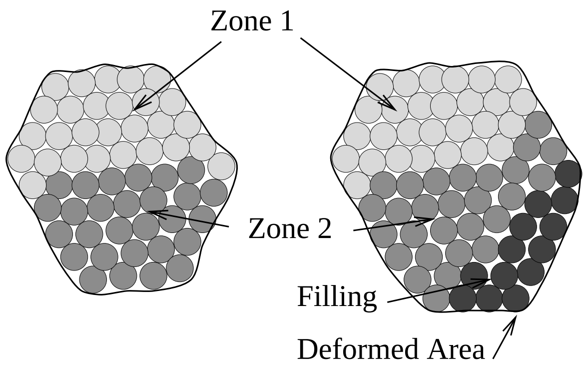


Figure 6: Example of deformation

3.2 Examples of animation

A deformation simulation of a particle-based object under the action of another particle is presented on figure (7). The volume remains constant during the deformation, since the particles of the lower object can not overlap. The cohesion is obtained with a spatial attraction force.

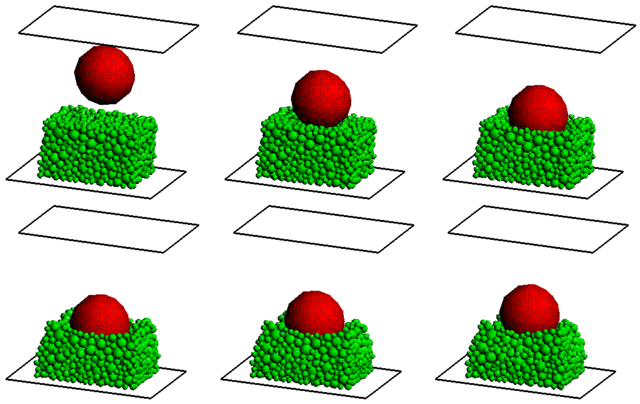


Figure 7: Deformation simulation

Figure (8) illustrate the break of a object falling on a rigid obstacle. When the cohesion force is not strong enough, the particles can detach from each other and the objects breaks into several parts.

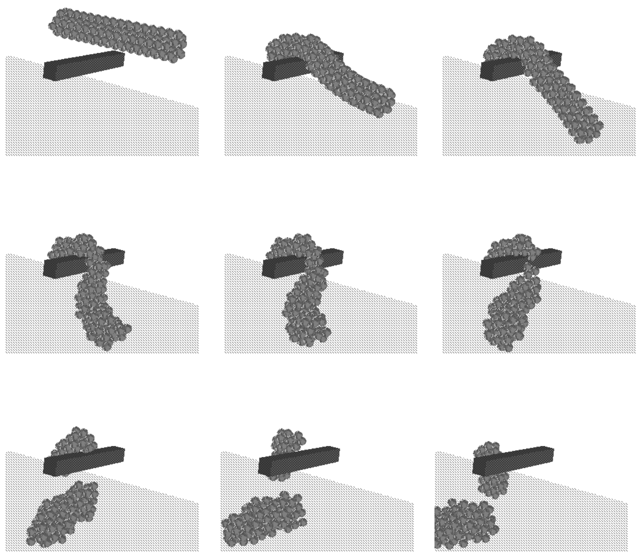


Figure 8: Break simulation

4. CONCLUSION

We have presented an original approach to model deformable objects with a particle system. This model seems to be well adapted to be integrated in a much more complete model of the internal and external shapes of the human body.

Oriented particles (Szeliski and Tonnesen, 1991) could be used to model the external surface (the patient's skin). Thus, the global model is homogeneous and very simple since it is only made of particles, run by the laws of physics. Despite of their simplicity, a wide range of complex shapes could be modeled including objects with branches or holes.
Moreover, various behaviors can easily be simulated. In the scope of our medical application, we simulate the dynamic behavior of internal organs with the particle systems. This will permit to adjust the parameters of the model by comparing the animation with the images sequences obtained from a X-ray simulator.
The use of particle systems avoids the difficult problem of the collision forces calculation and the precise computation of contact surfaces between the objects defined by finite elements or implicit functions (Desbrun and Gascuel, 1996). On the other hand, the implicit functions can be used to improve the quality of the display.

ACKNOWLEDGMENT

This work was supported in part by EC Framework IV, BIOMED II, contract BMH4-CT95-0567, project INFOCUS.

REFERENCES

S. Cotin and H. Delingette and N. Ayache, 1996, "Volumetric deformable models for surgery simulation of non-rigid organs", *4ème séminaire du groupe de travail Animation et Simulation.*

M. Desbrun and M.-P. Gascuel, 1996, "Smoothed particles: a new paradigm for animating highly deformable bodies", *Proceedings of the 7th Eurographics Workshop on Animation and Simulation, EGCAS Poitiers'96.*

J.-C. Lombardo and C. Puech, 1995, "Oriented Particles: A Tool for Shape Memory Objects Modeling", *Graphics Interface'95*, Quebec City (CAN).

M. Neveu and D. Faudot and B. Derdouri, 1995, "Superquadriques-B-déformables pour la reconstruction 3D", *Technique et Science Informatiques* vol.14(10), pp. 1291-1314.

J. Park and D. Metaxas and A. Young, 1994, "Deformable models with parameter functions: application to heart-wall modeling", *Proc. of IEEE Conf. on Computer Vision and Pattern Recognition (CVPR)*, Seattle, WA, pp. 437-442.

J. C. Platt and A. H. Barr, 1988, "Constraint method for flexible models", Proceedings of SIGGRAPH'88, pp. 279-288.

E. Promayon and P. Baconnier and C. Puech, 1996, "Physically-based deformations constrained in displacements and volume", *Eurographics'96, Poitiers*, pp. C155-164, Computer Graphics Forum, vol 15(3).

W. T. Reeves, 1983, "Particle systems: a technique for modeling a class of fuzzy objects", *Proceedings of SIGGRAPH'83*, pp. 359-376.

K. Shimada and D. C. Gossard, 1995, "Bubble mesh: automated triangular meshing of non-manifold geometry by sphere packing", *Third Symposium on Solid Modeling and Applications*, Salt Lake City, Utah, pp. 409-419.

R. Szeliski and D. Tonnesen, 1991, "Surface modeling with oriented particle systems", *Technical Report CRL 91/14*, DEC, Cambridge Research Lab.

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