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Deformable Objects Modeling and Animation: Application to Organs' Interactions Simulation

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Abstract. In this paper we describe a methodology for the calculation and animation of volumetric deformable objects. The goal of this work is to obtain realistic models of internal organs in order to simulate their motion and their form alteration during a radiotherapy process. Thus, these models should be able to represent the internal movements due to rhythmic motions, respiration, filling/emptying processes and organs' interactions. So we show how this can be done using particle systems and implicit surfaces and how to mix both models in an hybrid scene making organ's interaction simulation easier.

Key Words: deformable objects, particle system, implicit surface, surgery simulation

MSC 2000: 68U05

1. Introduction

In the medical area, digital imagery techniques provide Computer Tomography CT scan sections of internal and external structures of human anatomy. From a set of slices, the difficulty lies in the shape reconstruction of an organ, as well as in its deformation. The most widespread way is an optimal triangulation, but this method introduces a large number of triangles which may be inadequate for real time manipulation. Therefore, some authors have proposed to fit the triangulation with a smooth surface to reduce the data and improve the visualization [4]. In some cases, the contours have been directly fit by a smooth surface [9, 5]. But these models have been developed only for the purpose of rigid modeling and visualization. If the modeling of rigid objects has been largely discussed in the literature, few works have been presented in the domain of automatic volumetric deformable model reconstruction. An interesting approach is proposed by Cotin et al. [2], where the organ

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is first reconstructed with tetrahedra, using a simplex mesh method, to produce deformable models for surgery simulation. Deformable superquadrics are another one of the useful models for non-rigid surfaces since they can be deformed both locally and globally [10]. Nevertheless, these methods are only adapted for the modeling of a restricted class of objects. Implicit surface is another alternative technique for the modeling of deformable objects. It is very simple and allows to model very complex shapes [1]. With this technique, an object is described by a skeleton and a field function. The object's local deformation can easily be achieved by a local modification of the field function [3]. However, shapes obtained by union or blending between several implicit surfaces are not easily deformable. Some methods use articulated skeletons. This allows global shape alterations. Another interesting technique for the modeling of deformable objects is the particle system. It has been used in the purpose of geometric reconstruction. In [12], lines, surfaces and volumes are filled in with particles to obtain a spatial mesh, called bubble- mesh. Particle systems have also been widely used to model deformable surfaces in different applications. In [13], the authors propose a surface model with oriented particles, which allows joining, cutting and extending of deformable surfaces. Particle systems have also been used to model deformable volume objects. In [7], Lombardo and Puech describe a way to model deformable objects, and particularly muscles, with oriented particles and implicit surfaces, and Meseure and Chaillou [8] apply the particle systems to the simulation of the dynamic behavior of human organs . In this paper, we show how the last two models, implicit surfaces and particle systems and especially multi layer particle systems, can be used for modeling deformable objects. Since reconstruction methods have already been proposed for these models in [6] and [11], in this paper we detail the simulation and deformation process. So, in Section 2, our approach on animation and deformation of implicit surfaces are explained, and the limits of this model are shown. Then, in Section 3, we explain how multi layer particle systems can avoid these limitations. In Section 4, we introduce the principle of an hybrid scene using the both model. Some results are given in Section 5.

2. Deformable objects with implicit surfaces

2.1. Model description

The general formulation of an implicit surface S is :

$$S = \{p \in \mathbb{R}^3 \mid F(p) = 0\}$$

But, in computer graphic area, a more convenient formulation is used. This is the skeleton based approach which consists in describing the implicit surface by a skeleton and a field function. A skeleton is a set of geometric primitives s_i, called skeletal elements, for which a distance to a point is defined. Then, a field function f_i is associated to each skeletal element. f_i is a decreasing function of the distance to the skeletal element s_i. Then, the surface is generated by the functions f_i with a combination function g and by giving an iso-potential value ISO:

$$S = \{p \in \mathbb{R}^3 \mid g(\ldots, f_i(p), \ldots) = ISO\}$$

where g is generally the SUM or the MAX function. In [11], a field function and a 3D skeleton composed by a set of triangles is computed from a set of point organized in parallel sections. We use this reconstruction method because it gives good results in a reduced computing time.

2.2. Animation and deformation

For the animation and the deformation of implicit surfaces two steps are required. First the collision and the collision area on the surfaces in contact are identified. Next, the resulting contact forces and torques are calculated to permit the alteration of shapes due to these external constraints.

2.2.1. Collision detection

For collision detection of two implicit surfaces, we use a sampling method. Therefore, we first sample the two surfaces. Then, using the potential functions, we test if sampled points of one surface are included in the other surface. When such points exist, a collision has occurred.

2.2.2. Physically based animation and deformation

For a realistic simulation of the modeled organs, we use physically based animation techniques. The classic techniques [3] based on the detection of radial forces do not give satisfactory results. A more realistic technique should take into account the general force and torque components. For this purpose, we have developed a new methodology and we have distinguished two types of cases. In the first case, we consider organs as rigid. So we reduce the inertia parameters of the implicit surface to the parameters of its skeleton. The mass of the organ is equally distributed on the vertices of the skeleton. The inertia center and matrix of this skeleton can then be computed. When a collision occurs, a reaction force is applied to the projection of the collision point on the skeleton. Then, Newtonian laws are used to compute the linear velocity of the object, considering that all external forces are applied to the inertia center. Moreover, the generated angular velocity is computed from torques. These velocities permit to compute the rigid movement of the skeleton, and consequently the movement of the modeled organ. But, most of the organs are deformable. Thus, we have considered the skeleton as a deformable mass/spring system (a simplified particle system). When a collision occurs on a surface point, the reaction force is distributed on the skeleton's triangle that nearest to this point. Vertices' velocity is then obtained by integrating these forces. The movement of the vertices deforms the skeleton, inducing the deformation of the object's surface (see Fig. 1). However, only small deformations that do not modify the object's topology can be easily handled. Indeed, a large deformation of the skeleton will make the corresponding surface incoherent. This type of deformations generally involves the re-computation of the skeleton. This solution may be unacceptable in a real time context.

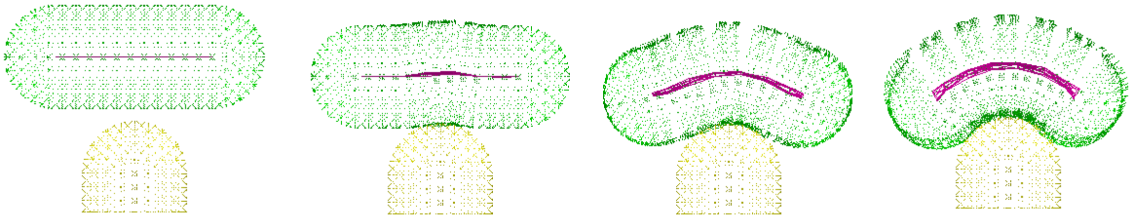

Figure 1: Animation and deformation of an implicit surface and its skeleton

3. Deformable objects with multi layer particle systems

3.1. Model description

A particle system is a simple model that consists of a set of interacting particles. To model an object with this model we have just to fill its volume with particles. In the aim of reducing the number of particles, the notion of layer was introduced. It consist in using big particles in the center of the object to fill a large part of the object volume with a small number of particles, and then reducing the size of the particles near the object's boundaries, increasing the precision of reconstruction [6].

3.2. Animation and deformations

Particle system are well adapted for animating deformable objects. The particles are subject to physical forces, internal forces or collision forces, that induce their movement. Thus, these forces will determine the particles displacement, and by extension the object's shape alteration.

3.2.1. Physically based animation and deformation

Particle system animation is simple. Each particle has a mass, and is subject to forces, so we just have to apply the Newtonian mechanic laws to generate the movement of the particles. We can distinguish several types of forces:

- external forces, that define the environment in which evolve particles (gravity, collision with obstacles, damping ...).
- internal forces that ensure connexity or volume preservation (attraction/ repulsion, auto-collision). Then, the movement of all the particles imply the movement of the modeled object, and the relative movement between particles generates the deformations. It is possible to handle a wide variety of behaviors, simply by changing force formulation and its parameters.

Small deformations: When we consider that the organs are not "very deformable", we can exploit the neighborhood of the particles to compute the forces. This reduces greatly the complexity of the system. The interaction between particles is then simplified and modeled with the help of springs that can be written in the following formula:

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

where k_s and k_d are the spring and damping constants, l is the initial length, r and v are the relative position and velocity of two adjacent particles. The constants defines the characteristics of the organ: rigidity depends on k_s, while deformability depends on k_d. This permits to model different behaviors from rigid to elastic state. Elastic and inelastic deformations can also be handled by a combination of simple springs. Cutting may also be easily simulated by removing springs in contact with the cutting tool. That can be very interesting for surgery simulation.

Adaptive animation: For very deformable object, the spring system is no more sufficient. We replace springs by general interaction forces like Lennard-Jones force to model internal interaction. The repulsion makes the particles slip on each other. Therefore, volume preservation is very easy to handle. For example, a bladder which is a bag filled by liquid and gas, can be simulated with this model. When they are changes in the topology of the object, the layer's structure may be altered. To prevent this to happen, we have developed an adaptive deformation method. The idea is to subdivide big particles in smaller ones when they are in contact with the external world. That permits to maintain the coherency of the multi- layer organization. While subdividing, it is important not to introduce perturbation in the system: volume and energy must be preserved. This is achieved by replacing a particle P of radius R, mass M, and velocity V, by n particles pi of radius

$$R' = \frac{R}{n^{\frac{1}{D}}} \quad (D \text{ is the dimension, 2 or 3}).$$

For a minimal volume loss, we use a face centered cubic (hexagonal in 2D) packing of the new particles which is the more compact packing of spheres (see Fig. 2).

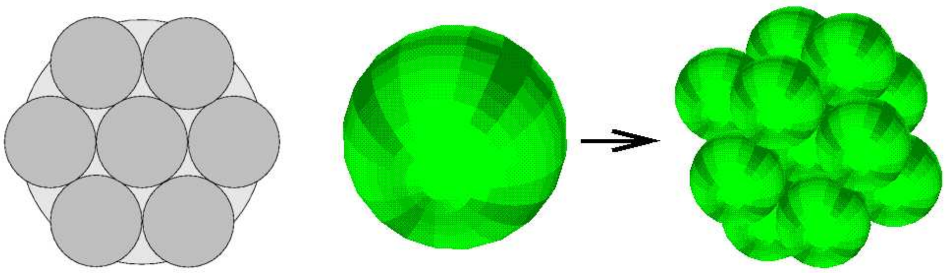

Figure 2: 2D and 3D subdivision of a particle

Regards to the movement quantity and kinetic energy conservation, each new particle must have the same velocity V than the subdivided one, and a mass m equal to the n^{th} of M:

$$\sum_1^n (mV) = \sum_1^n \left(\frac{M}{n}V\right) = MV \quad \text{(movement quantity)}$$

$$\sum_1^n \left(\frac{1}{2}mV^2\right) = \sum_1^n \left(\frac{1}{2}\frac{M}{n}V^2\right) = \frac{1}{2}MV^2 \quad \text{(kinetic energy)}$$

The evolution of a 2D object cut by a tool is presented in Fig. 3.

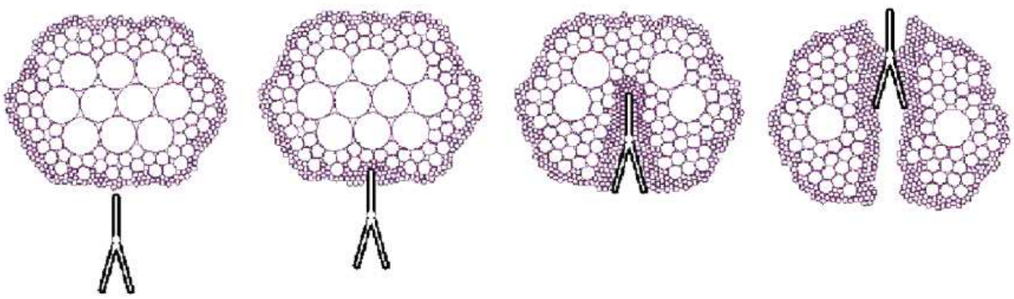

Figure 3: Evolution of the cutting of an object

4. Hybrid model

In previous sections, we have described how particle systems and implicit surfaces can be used to model deformable objects like organs. Using particle systems for modeling all the organs is very expensive in computing time and memory size. In the other hand, implicit surfaces cannot simulate large deformations. This make them undesirable for the simulation of some behaviors. The key idea is to use both models. Therefore, particle systems will model organs that are subject to large deformations, and implicit surfaces for the others.

4.1. Interaction between particle systems and implicit surfaces

To use and animate two models simultaneously, we have to handle eventual interactions between them. To this end, we first define a collision detection method between a particle system and an implicit surface. Rather than using the sampling based method described above (Section 2.2.1), which needs to test the distance between all the sampled points on the implicit surface and all the particles, we proposed a new method based on the surface potential function. For each skeletal element and for each particle, we compute the closest point on the particle with respect to this element. Then, for each of these points, a local potential due to the corresponding skeletal element is computed. We combine these values using the combination function g of the implicit surface defined in Section 2.1. The result is the maximal value of the potential of a particle's point. So, if this value is less than the ISO-potential of the surface, we are sure that there is no collision between the particle and the surface. In the other case, a collision is possible. If the combination function is the *MAX* function (which is our case), we are sure that a collision has occurred. If the combination function mixes the values, like a *SUM* function, we propose an heuristic which consists in computing the weighted barycentric combination of the previously computed points. The weights are the normalized values of the local potentials associated to these points.

Then, we project this point on the particle's surface, and we compute the potential value of the projection. The comparison of this value with the ISO-potential of the surface permit us to determine whether there is a collision or not (see Fig. 4). This heuristic works efficiently in most cases. For collision detection with a particle system we have just to apply this method to each particle. We can reduce the number of particles that can collide the surface to those included in the intersection of the bounding boxes. When a collision is detected, a reaction force is computed and applied to the particle and to the implicit surface. Then, the two models are animated and deformed as described in previous sections.

5. Examples

Fig. 5 (left) shows an hybrid scene, composed by a bladder(up) and a rectum(down) modeled with particles and a prostate modeled with an implicit surface, used for studies of the relative movement of these organs for cancer radiotherapy. And Fig. 5(right) shows a more complex hybrid scene for the lungs movement studies.

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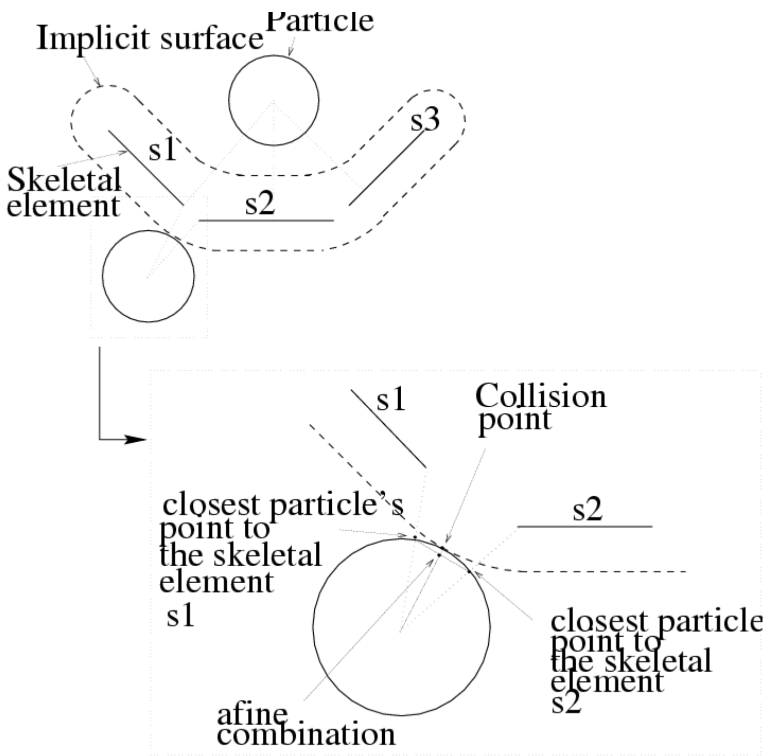
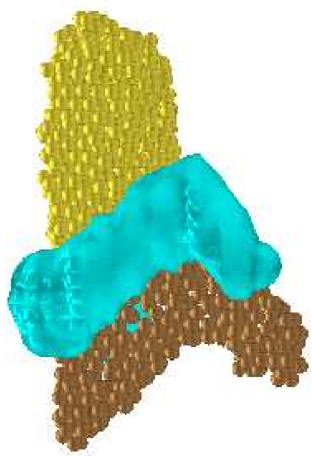


Figure 4: Collision detection between a particle and an implicit surface



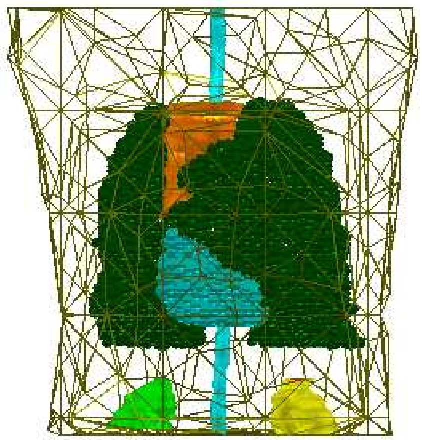


Figure 5: left: Bladder (particles), prostate (implicit) and rectum (particles), right: An hybrid model of human body shape (implicit) and internal organs (implicit and particles)

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