DEFORMABLE OBJECT RECONSTRUCTION WITH PARTICLE SYSTEMS

F. Jaillet, B. Shariat, D. Vandorpe

LIGIM, bâtiment 710, Université Lyon I, 43 bd du 11 nov. 1918
69622 VILLEURBANNE Cedex, FRANCE

In this paper, we describe a general method for reconstruction and animation of volumetric deformable objects. First, the initial data, defined by planar contours, are fitted with a closed periodic parametric surface. Then, this rigid model is used as a closed boundary, which is filled in with particles. For this, new particles are progressively generated within the boundary. When a new particle is introduced, there will be an interaction between this particle and all the existing particles. They will also collide the boundaries. Then we let the system evolve under physically-based forces, until the particles reach an equilibrium state. We have defined some simple rules for the new particle generation. In the scope of a medical application, we want to simulate the motion and the form alteration of the internal anatomical organs. Hence we have introduced the necessary tools to handle the dynamic and deformable behavior of cancerous organs.

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.

There are two major problems. The first one is a geometric problem concerning patient movement and alterations in shape and position. The second one is the problem of vastly increasing information: to perform conformal therapy in a moving environment, informations from a number of disparate sources must be used simultaneously by the physician. To solve the first problem it is

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necessary to create two 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 internal and external forms are dynamic and deformable, subject to internal and external forces, especially due to the natural rhythmic motions 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 systems 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 some cancerous tumors.

The initial available data for the reconstruction of the desired forms is a set of 2D contours. Therefore, after a brief study of the art in section 2, we have introduced, in section 3, a parametric closed surface reconstruction method to obtain an initial static volume model from 2D sections. In section 4, we use this closed surface model to calculate a static model based on particle system. In section 5, we introduce necessary tools for the animation of the organs. Some examples will illustrate the quality of obtained results.

2 Related work

In the medical area, digital imagery techniques provide CT scan sections of internal structures of human anatomy. From a set of planar slices, numerous algorithms have been proposed to reconstruct the surface of an organ. The most widespread way is an optimal triangulation, but this method produces a large number of triangles. Therefore, some authors have proposed to fit the triangulation with a smooth surface to reduce the data and improve the visualization [3]. But these models have been developed only in the purpose of rigid modeling and visualization. Also, numerous methods have been presented to handle deformations of 3D objects. Deformable superquadrics are one of the useful methods in non-rigid surface modeling since they can be deformed both locally and globally [9]. Nevertheless, these methods are only adapted for the modeling of a restricted class of objects.

Another interesting technique for the modeling of deformable objects is the particle system, which has been introduced in [11] to model fire and explosion with non-interacting particles. Particle systems have been widely used to model deformable surfaces in different applications. In [13], the authors propose a surface model with oriented particles, which allows to easily join, cut and extend 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 apply the particle systems to the simulation of the dynamic behavior of human organs [8].

If the modeling aspect has been largerly discussed in the literature, few works have been presented in the domain of automatic volumetric deformable model reconstruction. Particle systems have 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. An interesting approach is proposed in [1], where the organ is first reconstructed with tetrahedra by using a simplex mesh method, in order to produce deformable models for surgery simulation.

3 Surface reconstruction with B-splines

Our goal is the reconstruction of a smooth closed surface from planar contours (usually CT scan sections). In figure (1), an example of these contours is given. To fit a closed surface to these sections, we proceed in three steps:

- First, we approximate each contour with an open B-spline curve with degree k and $m+1$ control points P_i , with $i = 0, \dots, m$.
- Second, we transform these curves to obtain closed periodic B-spline curves of equation:

$$P(u) = \sum_{i=0}^{m} P_{i\,mod(m+1)} N^k_{i\,mod(m+1)}(u) \ \text{ with } u \in \mathbb{R}$$

  For this, we add $(k-1)$ control points $P_{m+i} = P_i$, for $i = 1, \dots, k-1$, and the new uniform knot sequence is:

$$-\frac{k-1}{m}, \ \dots, \ -\frac{1}{m}, \ 0, \ \dots\dots, \ 1, \ \frac{m+1}{m}, \ \dots, \ \frac{m+k-1}{m}$$

  The periodicity ensure a C^{k-1} continuity at low cost, for spline of degree k. To obtain the same result with a non-periodic B-spline it is necessary to impose strong derivatives constraints on control points.
- Third, we approximate the control points $P_{i\,mod(m+1)}$ in the other direction to create a closed biparametric B-spline surface of degree $k \times l$.

$$P(u,v) = \sum_{j=0}^{n} \left[\sum_{i=0}^{m} P^j_{i\,mod(m+1)} N^k_{i\,mod(m+1)}(u) \right] N^l_j(v) \ \text{ with } u \text{ and } v \in \mathbb{R}$$

  For more details see [5].

Results

The initial data are 26 planar slices, with more than 4000 points (Fig. 1). We have reconstructed this object with a periodic spline surface of degree 2 and 15×20 control points (Fig. 2). This has permitted to reduce dramatically the amount of the initial data. To close the surface model, in order to obtain a volume model, we have introduced arbitrarily two points at the top and the bottom of the given sections. These points represent two supplementary sections reduced to one point.

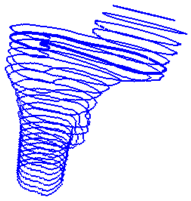


Fig. 1. Contours of the object

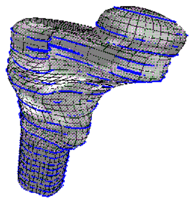


Fig. 2. Reconstructed spline surface

The proposed reconstruction method of closed anatomical objects is very simple. It permits to represent smooth and regular shapes. The degree is independent of the number of data points. It is C^{k-1} continuous and the model could be refined by adding some control points. However, the patient moves during the treatment and the simulation of the organ's biomechanical behavior is difficult to handle with a biparametric model.

4 Volume modeling with particle systems

Since anatomical organs to be reconstructed are dynamic deformable forms, we need a new model which can take easily into account the organ's movements and alterations during the treatment. Particle system is a very interesting tool for this purpose.

4.1 Particle systems

A particle based model is composed of solid spheres in interaction. Our proposed parametric surface reconstruction method supplies a model that will be filled in with particles. The particle model seems to be a good compromise between display time, realism and memory occupation, since the required precision is not high (about 1 mm). Moreover, the collisions and the reaction forces are easy to handle, because particles are driven by Newtonian laws of physics [15]. In this model two types of forces are considered:

– internal forces which represent the interaction between particles. This can be defined by spatial interaction forces whose magnitude depends on the distance between two particles (attraction/ repulsion)
– external forces, like collision with obstacles or gravity, which act independently on each particle

4.1.1 Interaction between particles during reconstruction

To model the interaction and ensure the cohesion between particles, we use the classical *Lennard-Jones* potential law and its derivative force:

$$E(r) = \frac{\varepsilon}{m-n}\left[m\left(\frac{r_0}{r}\right)^n - n\left(\frac{r_0}{r}\right)^m\right] \quad \text{and } \boldsymbol{f}(r) = \overrightarrow{grad}\,(E(r))$$

where r_0 is the stability distance, r the distance between particles, ε the amplitude, n and m two intuitive parameters that define the aspect of the graph of $E(r)$ (often n=2*m). Unfortunately, this force introduces oscillation around the stability position. Therefore some authors have proposed new forces to avoid oscillations [7].

4.1.2 Response to collision with obstacles

To keep the particles within a closed boundary we use a collision force. The detection problem of the collision of a particle with a boundary could be reduced to a problem of distance between a sphere and a plane. Figure (3) illustrates the collision response defined by the particle's velocity after collision $\boldsymbol{v} = \boldsymbol{v}_t - r.\boldsymbol{v}_n$ in which r is the restitution coefficient. If a particle is colliding with the contour with normal velocity, $\boldsymbol{v}_n$, equal to zero ,then there is contact (Fig. 4) and the applied force is $\boldsymbol{f}_c = -(\boldsymbol{n}.\boldsymbol{f})\,\boldsymbol{f}$, so the particle slips along the contour.

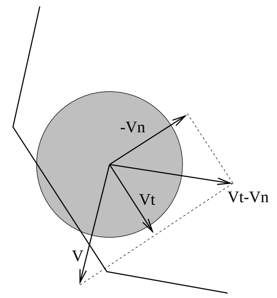


Fig. 3. Collision response

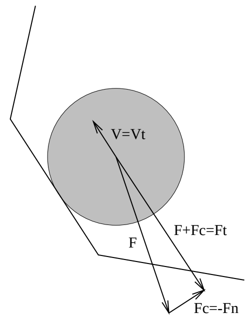


Fig. 4. Contact response

4.2 Volume reconstruction with particles system

The aim is to reconstruct a volume from 3D boundaries defined with spline surfaces or polyhedral faces. We propose a model able to reconstruct a large variety of shapes (with branches or holes). The reconstruction principle is to fill in the reconstructed static volume with particles. In order to minimize the number of the generated particles while respecting some precision criteria, we begin with big particles in the center of the object. When approaching the boundary, the particles' size and mass are reduced to better approximate the boundary. Thus, the multi-layer volume reconstruction process is composed of the following steps:

- Particles initialization
- Repeat until the desired precision is obtained :
  - New particle's parameter determination and its generation
  - Interaction and collision forces calculation
  - Calculation of the particles' position by integrating forces

This method allows a maximal filling which is important to model easily volume conservation applied to anatomical shapes.

4.2.1 Particles in layers

We use a particle system as described previously. Each particle is defined by a position P, a velocity $\boldsymbol{v}$, external forces $\boldsymbol{f}$, a radius R, a mass m, proportional to the volume, and two distances to the boundary d_1 and d_2.

The distance parameters are introduced to model particles in layers (Fig. 10) as described in [6]: a skin for cohesion, around a derm for deformability, around a nucleus for shape approximation. The d_1 parameter prevents the big particles to be too close to the boundary, while d_2 prevents the little ones to be too far. $(d_2 - d_1)$ is the width of each layer. This model permits to greatly reduce the number of particles. This is illustrated for the 2D case on figures (5) and (6). The nucleus is modeled first with big particles and a large parameter value d_1 to keep them far from the boundaries and then the radius of the particle as well as the value of d_1 and d_2 are reduced to allow the smaller particles to get closer to the boundaries, in order to refine the object's shape.

4.2.2 Particle generation

In order to fill a region with variable size particles, we initialize the process by creating big particles inside the boundary. Next, we define simple rules for new particles generation around these first particles. This will permit to decrease

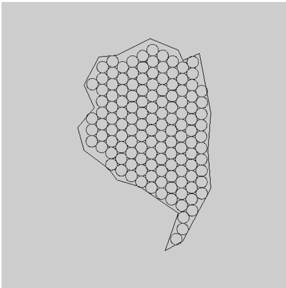


Fig. 5. Mono-layer : rough approximation with 134 particles

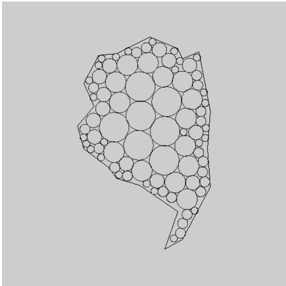


Fig. 6. Multi-layer : better reconstruction with 82 particles

the number of particles while increasing the precision of the obtained model. These rules are:

(i) New particles should not perturb the system, they should be introduced close to motionless existing particles.

(ii) In order to prevent the "explosion" of the particle system, particles should be created near the equilibrium position (Fig. 7). We consider a sphere of radius $d = \alpha(R + R_c)$ where R is the radius of the existing particle, R_c the radius of the one to be created and α the proximity coefficient. When $\alpha = 1$, the particles are tangent and for $\alpha < 1$ the particles will overlap, allowing to create more particles but making the system less stable. Then we randomly choose points P_c on this sphere, that could be potential positions for new particles, and next we check if no other particle P', with radius R', stands at the position satisfying the condition $dist(P', P_c) \geq \alpha(R' + R_c)$.

(iii) Next we have to verify that particles are not generated too close to the boundary: $dist(boundary, P_c) \geq R_c + d_{1c}$. In the same way, they should not be created too far: $dist(boundary, P_c) \leq d_{2c} - R_c$, where d_{1c} and d_{2c} are the minimal and maximal allowed distance to the boundary for each created particle.

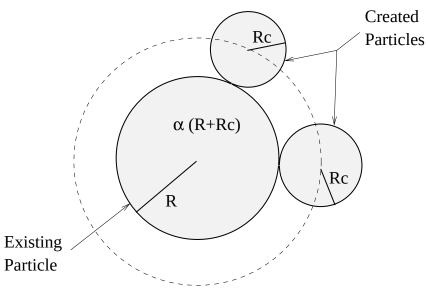


Fig. 7. New particles generation

The particles' motions are controlled by physical laws. Each time a particle is added, all the particles will interact until they reach an equilibrium. We calculate the new particles' position p at time $t + dt$ by integrating the forces

$\boldsymbol{f}$ and the velocity $\boldsymbol{v}$ at t, with an first order Euler's method:

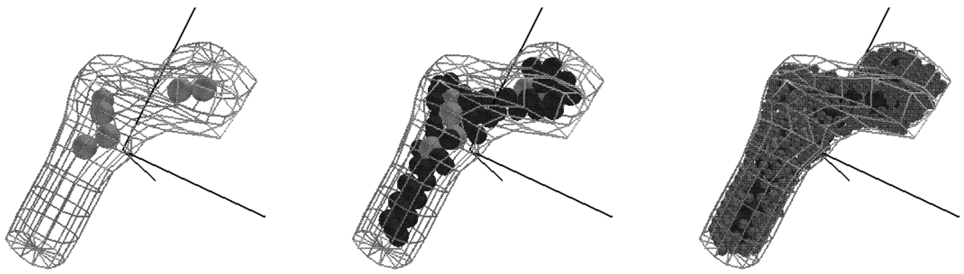
$$\boldsymbol{v}(t+dt) = \boldsymbol{v}(t) + \boldsymbol{f}(t)/mass * dt \quad \text{and} \quad p(t+dt) = p(t) + \boldsymbol{v}(t) * dt$$

When we have a stable position for all particles and it is no more possible to create a new particle, the radius (as well as the mass, proportional to the volume) and the repulsion field are decreased. Then, we iterate until we reach a defined minimal threshold for the particles' size. We show the evolution on figure (8).

(a) 7 particles (b) 32 particles

Fig. 8. Evolution of the reconstruction of a square

The figure (9) shows the same evolution but in 3D, for boundaries representing the same object as in section 3.



(a) 6 particles (b) 39 particles (c) 253 particles

Fig. 9. Evolution of the reconstruction of a 3D object

5 Dynamic simulation of objects deformation

In the previous section we have defined a particle model of deformable objects on which alterations of forms can easily be handled. The alteration is induced by the presence of obstacles resulting in local displacement of the particles representing the "skin". Consequently, this movement will be propagated through the whole system permitting the calculation of the new form. The internal links between the particles are defined with the help of springs or spatial interaction forces.

5.1 *Formulation of deformation with springs*

After the volume reconstruction phase, if we consider that the object is not "very deformable", we model the relationship between particles with springs and this greatly reduces the complexity of the system. Therefore, with springs we suppose that there is no important variation in the object's topology and consequently we have only neighborhood relationships between close particles. To calculate the force exerted on particle #2 by #1, we write:

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

where:

k_s	, spring constant	$\boldsymbol{r}$	$= \overrightarrow{P_1P_2}$
k_d	, damping constant	$\boldsymbol{v}$	$= \boldsymbol{v_2} - \boldsymbol{v_1}$

The constants define the characteristics of the material: rigidity depends on the spring's constant and the deformability on the damping constant. These two parameters allow to model different materials like superball or clay. But the springs tends to increase the resistance of the object, and important deformations are not allowed. To solve this problem the spring can be removed when the elongation is greater than a cohesion threshold and then the object can break into parts, simulating fracture behavior. In [14], elastic and inelastic behavior are simulated easily by combining simple elastic, viscous and plastic units.

5.2 *Formulation of deformation with spatial deformation force*

For "very deformable" objects, we may replace the springs by simple contact forces like Lennard-Jones force to model the internal interactions of the object. This force is divided in two parts : a short range repulsion and a long range attraction. The Lennard-Jones force is used when there are constraints on deformations. For example the repulsion force prevents the particles to overlap, they slip on each other. Therefore, constant volume deformation can be modeled easily. Other constraints can be defined like elasticity, malleability [10]. In our application, we are defining the characteristics of the organs, and consequently the particle system parameters, in cooperation with physicians (from Christie Hospital in Manchester, U.K.).

6 Conclusion: towards a complete dynamic model

We have presented a new reconstruction technique of deformable objects with particle-based system. This can easily permit the modeling of complex interacting internal organs with heterogeneous behaviors (Fig. 10). B-spline surfaces may be used to model the external shape (the patient's body), but as the required precision is not very large, we prefer to use oriented particle systems for surface modeling as presented in [13]. Moreover, the calculation of the deformation, using particle model is very simple because it comprises only particles driven by n-ary or spatial interaction forces.

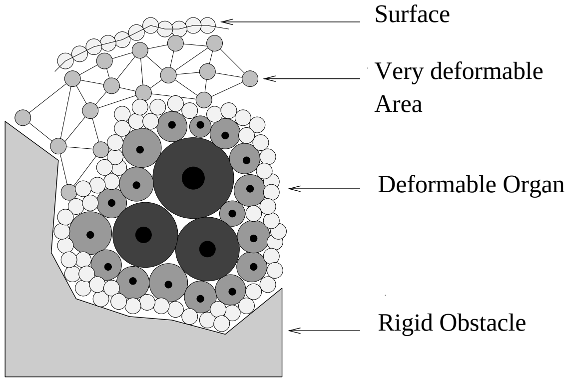


Fig. 10. Complete model

The use of particle systems will avoid the difficult problem of the calculation of collision forces and contact surfaces between objects defined by finite elements or implicit functions as studied in [2].

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