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Robust segmentation of anatomical structures with deformable surfaces and marching cubes

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Abstract

Computer assisted medical applications require often the reconstruction of anatomical structures to compute parameters useful for diagnosis or interventional planning. From CT and MRI datasets it is possible to obtain surface models of the organs of interest with a variety of algorithms, like Marching Cubes, level sets or deformable parametric surfaces. Each technique has advantages but also drawbacks like noise sensitivity (isosurface extraction), risk of leakages (level sets), oversmoothing and impossible handling of topological changes (Deformable models). To obtain a good trade-off between robustness, shape constraints and topological control, we propose a 3D balloon/isosurface method joining the advantages in curvature control, leakage penalization and efficiency of parametric surfaces with a fast re-parametrization handling topological changes. It is based on the control of surface self-intersections, freezing of the intersected nodes and replacement of the final mesh with an isosurface computed on a field representing the signed distance from the true surface.

Keywords: Segmentation, Topology, Marching Cubes, Deformable models

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Line and Curve Generation

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1. Introduction

The automatic segmentation of 3D images is an important research field in Computer Vision and it is extremely relevant especially in medical applications due to the recent large availability of high resolution volumetric digital data provided by new modalities like MRI, multi slice CT, PET, etc. The recovery of the external surface of an organ is relevant for 3D visualization and can be used to support quantitative diagnostic measurements. However, this task may be challenging, even in the apparently easy case of visually uniform regions like vessels with injected contrast agent. In fact, the segmentation method should, in this case provide a closed surface, with smooth borders, avoiding leakages in neighboring contrasted structures but not missing bifurcations with smaller vascularizations. This means that the algorithm should provide a topology control, be robust against noise, the surface must be kept smooth, but not too much if we want to detect small structures or local pathologies.

To find a good tradeoff between all these requirements is really a difficult problem, and the variety of approaches and customized solution proposed show this fact clearly [KQ04].

Surface reconstruction methods proposed in literature have, in general specific advantages and drawbacks. Simple isosurface extraction [LC87] does not guarantee topology control and it is quite sensitive to noise. It is usually applied to organ reconstruction after region growing based binarization, but this procedure also suffers of noise sensitivity causing possible creation of holes and leakages. Holes and leakages are also a relevant problem for more advanced level sets or geodesic surfaces methods[MSV95, CKS95]. To prevent irregularities, holes and leakages the best approach is to use a parametric deformable surface instead of an implicit curve, with the same approach as the classic balloon snakes [LC93]. These methods (see [MT96] for a review of the first medical applications) are efficient and robust. The elastic forces avoid the surface block near a noisy pixel and prevent leakages. On the other hand, they may avoid the detection of small structures and have a fixed topology except in some modified versions like the T-Snakes of McInerey and Terzopulos[MT95], based on a continuous re-parametrization on a fixed grid. This makes the algorithm behave like a front propagation method, with higher complexity and possibility of leakages and unwanted topology changes.

It is evident that the limits of discretized meshes coincide with the advantages of level sets or periodically reparametrized surfaces and vice versa. The choice of the best algorithm to be applied usually depends on the application to be developed. In cases where the advantages of both methods are desirable, like in vascular segmentation, where topology control is necessary, leakages must be prevented, but small structures must be detected, and, in particular cases, complex topologies may occur, it is interesting to search for a reasonable mixture of the approaches to obtain better results. Several authors proposed therefore ad hoc combined methods. Magee and Bullpitt [MD01], for example, used level sets and deformable discrete surfaces together to recover the structure of Abdominal Aortic Aneurysms. Chen and Amini [Che04] also obtained a segmentation of vascular structures from MRI images with different steps, first applying multiscale enhancement, then level sets to describe the vascular volumes and finally building a triangulated model of the vascular surface using then an elastic evolution for the final refinement.

In this paper we propose a more general "combined" method that can be used for generic organ reconstruction being not specialized for vessels and not exploiting model based constraints. It is a simple 3D balloon method inspired by that implemented in [AGZ03, GZ04], where the basic mesh structure is a simple triangulation (no longer a simplex mesh), with forces applied to nodes in order to make the surface converge towards borders keeping it smooth and simple faces split/merge rules keeping face size approximately constant and related to the scale of the smallest structure to be detected. The problem of handling topology changes is solved through self-collision detection. When self-intersection is detected all the self intersected nodes are blocked and the system continues its evolution till the equilibrium is reached. At this point, the surface is reparametrized through a distance map computation and a marching cubes extraction on it. This simple combination provides a very efficient a robust segmentation tool successfully tested on synthetic images and medical data. The paper is structured as follows: Section 2 presents a quick description of the balloon algorithm, Section 3 describes the self-intersection detection and marching cubes based mesh recomputation. Section 4 presents experimental results that are finally commented in Section 5.

2. The balloon algorithm

The basic idea of balloon algorithms is to place a very small deformable bubble inside the structure we intend to segment, e.g. aorta, colon, etc. and then to inflate it, complying the following fundamental constraints/requirements:

- The bubble cannot grow beyond the border of the structures.
- The bubble cannot split: it will remain a single connected component until the end of the process.
- At the end of the algorithm, the bubble gives an accurate description of the surface of the structure

We implemented the bubble as a triangulated mesh. At the beginning of the process, the bubble is the approximation of a sphere obtained with a few triangles and of the approximate size of a single voxel. The bubble is then inflated approximating with an iterative node displacement a dynamic model where the mesh nodes are treated like masses and several forces are applied to each of them. The choice of the force terms and of their weight is fundamental to obtain a correct segmentation (i.e. a regular surface close to the voxels defining the organ limits).
In our model, like in classical 2D "Snakes" two "internal" forces are applied to the nodes to preserve connectivity and smoothness of the mesh.

The first term is a simple elastic force computed by considering all the edges as linear springs and the vertices's as mass points. The second term is added to prevent surface folding, by penalizing the abrupt changes of normal to the surface. This is done by applying to each vertex a force proportional to the dihedral angle on its opposite edge.

The inflation of the bubble is accomplished through a force directed as the local surface normal vector (see Figure 1.a). The magnitude of this force is inversely proportional to the difference between the local gray level and the reference value for the region to be segmented (local gray is obtained through tri-linear interpolation on the voxel data). When this difference exceeds a threshold the force becomes zero and this means that the vertex has reached his final position. We exclude therefore it from the further evolution in order to speed up the computation.

As the bubble grows, the triangles become bigger. Since the final goal of the process is to fit the bubble over the surface of the structure, it is self evident that the size of the triangles must be of the order of the size of the voxel. As a triangle grows more than a fixed threshold, we perform a mesh refinement, as in Figure 1.b, splitting the longest edge and adding two new triangles.

3. Self intersection

During the evolution, the mesh can intersect itself, because the anatomical structure to be segmented is not always topologically equivalent to a sphere. In this case the method as explained so far would not work properly providing a self-intersecting surface. Worse, if no intersection control is performed, the bubble will never find the equilibrium position, since it can inflate forever without increasing the

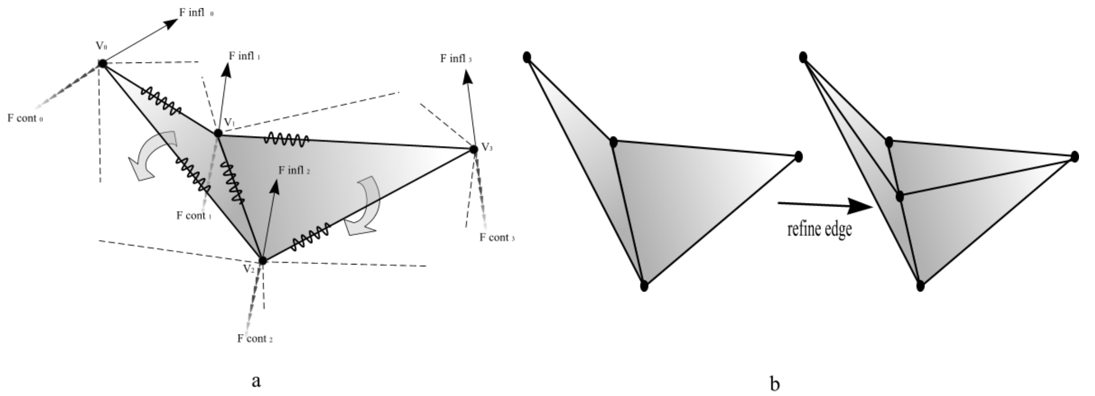

Figure 1: *a. Dynamics of forces acting on 2 faces.*F_{infl} *(inflating forces) are directed along normal of the vertex ,*F_{cont} *(containing forces) are their opposite. Others terms are added to each face penalizing the abrupt changes of normal to the surface. b. Each edge that becomes bigger than a threshold will be divided preserving accuracy of surface representation.*

occupied volume. We have already noticed that classical surface evolution algorithms that can change topology (i.e. level sets and T-Snakes) are computationally expensive and present other drawbacks (i.e. leakages) To restore a non self-intersecting surface (changing the topology if necessary) our solution is to perform a periodical collision detection in order to find intersecting portions of the surface and blocking the vertices belonging to intersecting faces.

The collision detection algorithm implemented is based on spatial hashing (see [THM*03] for details) and identifies all the nodes in the self intersecting part of the surface. Blocking the identified nodes evolution is sufficient to prevent the system form looping forever, so the surface can reach an equilibrium position. The resulting triangulated mesh is not, in general, a correct representation of the border of a volume, because of the self intersections, but it is still a watertight surface that defines which is the space inside the structure and which is the space outside the structure. This allows us to build a distance map computed on a regular grid (coincident in out implementation with the voxel grid) assigning to each voxel of the volume the signed distance from the closest non intersected face with a sign, which is negative if the point is inside the volume enclosed by the surface and positive otherwise. Due to the use of the part of the surface that is not self-intersecting (see Figure **??**), the result is that the iso-surface of value 0 of the map is a surface defining the limits of the region of our interest with no self-intersections and the correct topology. This surface mesh is easily computed by means of the marching cube algorithm [LC87], a classical solution to reconstruct an iso-surface, i.e. the surface where the scalar value is constant and equal to a specified value from a regular sampling of a scalar field. The only hypothesis of this algorithm is that the scalar field can be linearly interpolated from the values at the grid point.

The result of the isosurface extraction is a new triangulated mesh that replaces the old one. The new mesh is no longer self-intersecting and has a different topology (typically its genus has increased). The only problem of the new surface is that is not smooth and may not be close to the expected boundaries near the formerly self-intersecting region due to the approximations introduced in the distance map computation. These problems are easily solved with a surface refinement consisting of few steps of the deformable surface algorithm.

The final segmentation method can be summarized through the following steps:

1. Run simulation to inflate the bubble, blocking the part of surface that self-intersect.
2. When the system is at equilibrium, erase from the triangle mesh all the triangles belonging to regions that self intersects and compute a signed distance from the resulting mesh on the regular grid.
3. Run the marching cube algorithm to build the new mesh
4. Run some step of the simulation for a better fitting of the region involved in the topological change.

4. Results

We successfully tested our algorithm first on synthetic images of structures to validate the self collision detection/marching cubes method(see Figure4). In all the situations created, we obtained a closed smooth surface defining an internal region close to the voxelized volume of interest and with the same euler number.

The algorithm was then applied to CT scans of the abdomen in order to segment the vena cava and the aorta. Fig.**??** shows four steps during the surface evolution. The scale of the image is changed to keep the mesh visible during its growth. In this example, the resulting final mesh is made

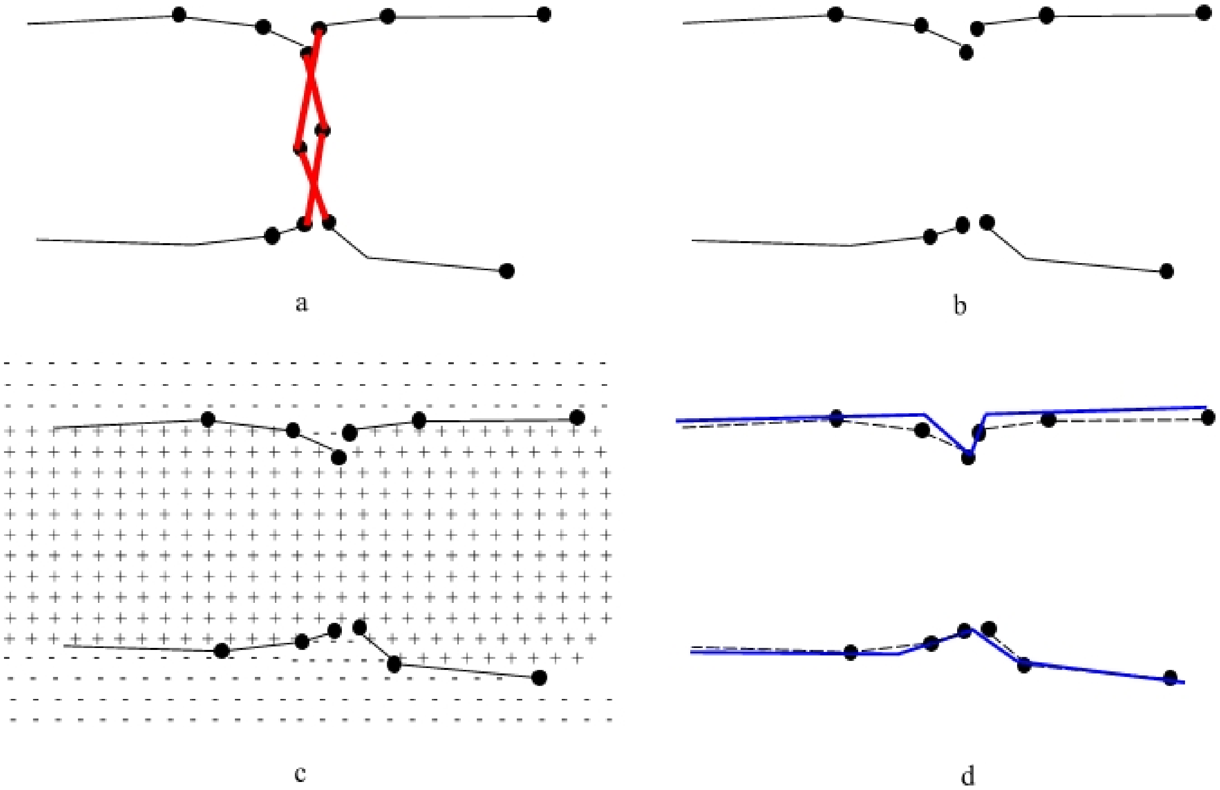

Figure 2: *a.Intersected faces are detected. b.Intersected faces are removed. c.For each voxel we compute the signed distance. d.At the end using Marching Cubes we obtain the new surface.*

of 62K triangles (this number is dependent on the volume detected and voxel size). However, the mesh can be post processed using common techniques of error preserving mesh simplification to get a more efficient representation.

In all the cases tested segmentation results were accurate and fast, no manual corrections were required and the only user intervention performed was the seed placement. The time needed to produce the vena cava model is about 30 seconds.

5. Conclusions

We presented a new technique for robust segmentation of anatomical structures from volumetric dataset. The technique is robust and general, and requires minimal user intervention. We indeed plan to remove all the user intervention for particular applications where the approximate position and the gray value of the contrasted organ is known. The algorithm can also be easily made parallel by setting different seeds, looking periodically for self-intersections and intersections with other meshes, stopping self intersected and intersected nodes and finally merging all the structures detected with the distance map/marching cubes approach. The accuracy of segmented structures will be tested on vascular structures already measured with other reconstruction methods and phantoms like in [AGZ03] All the code is written in ANSI C++ using the VCG library for the mesh processing (see http://vcg.sf.net). This project is developed in the framework of Endocas, the Italian Centre of Computer Aided Surgery.

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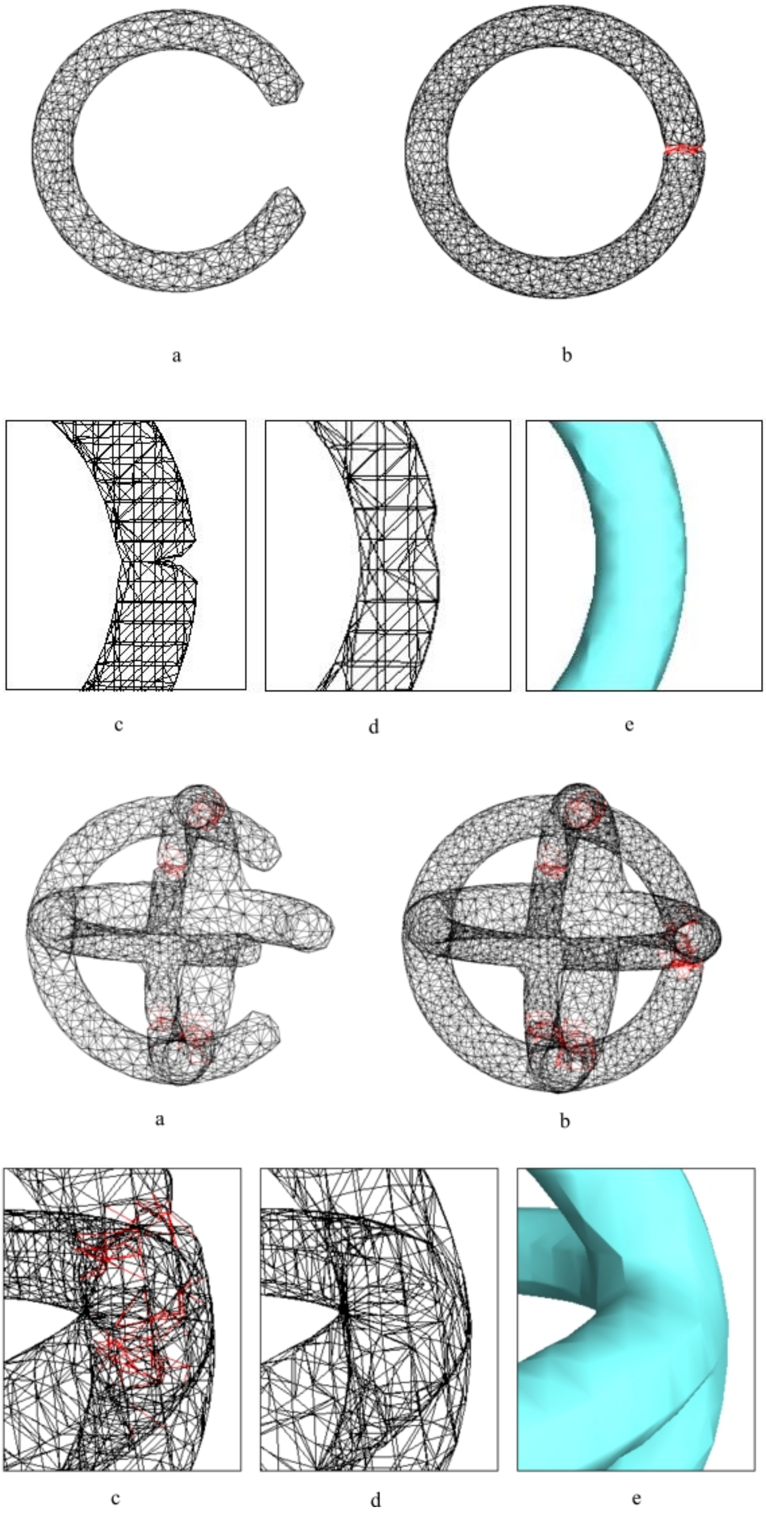

Figure 3: *2 Examples of self intersection managing: a.The bubble start to expand. b.The bubble fit the geometry and self intersection is detected (faces that generate self intersect are shown in red). c.d.e.Then using Marching Cubes and expansion steps we obtain the final triangle mesh.*

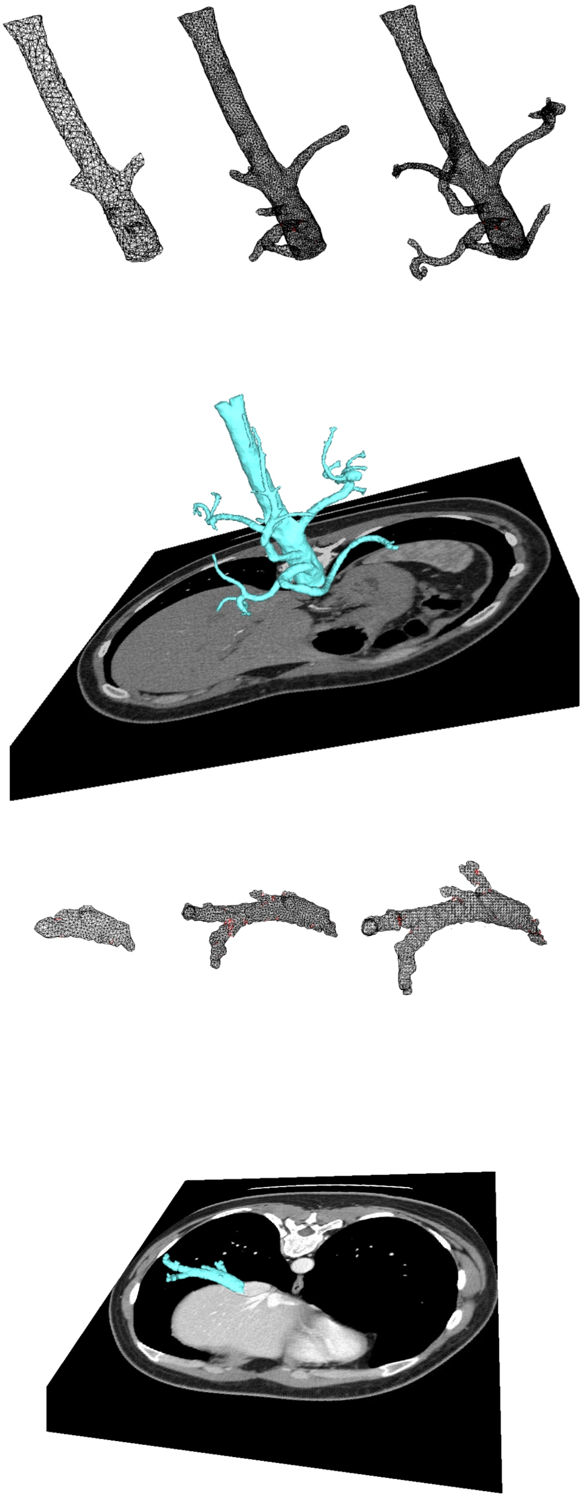

Figure 4: *Different phases of extraction of an aorta(on the top) and a vena cava(on the bottom).*