3D Segmentation of the Left Ventricle in Echocardiographic Images using Deformable Model based on the Geometric Evolution Shapes

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Abstract

This work presents a new segmentation method of volumetric echocardiographic images, using a 3D front propagation initialized as a small sphere that grows until arriving to the walls of the left ventricle (LV), adjusting the parameters to the model. The project is developed in three modules denominated: Acquisition, Segmentation and Visualization. 1) The images' acquisition of volumetric sequences of the LV was obtained in an echocardiographic test. 2) The segmentation was divided in three parts: a) A first segmentation method 2D->3D. It uses a front propagation method initialized with a circle that grows inside the acquired volume. b) A 3D front propagation initialized with a small sphere placed in the interior of the LV, which begins to grow occupying part of the ventricle cavity. c) The surface obtained previously is parameterized. The model is adjusted minimizing the energy of the error between the model and the segmentation carried out with the front propagation. The new idea of this work is the parameterization of the surface using an hierarchy of geometric shapes. With a few values of the model, we can capture the shape, size, position and torsion of the LV.

1. Introduction

The geometry and the movement of the left ventricle is considered very useful for the diagnosis of cardiovascular illnesses. These two properties of the LV have been able to detect congenital anomalies as: septal defects, chamber enlargement, and the diagnosis of ischemia as well as the arhythmias and infarctions. With the purpose to improve the medical diagnosis, the visualization and to obtain better echocardiographics images; a new workstation to acquisition was developed using a commercial two-dimensional echograph.

These images are captured by scanning the heart with the ultrasound sheaf. The method of transtoracic rotational sweep was used [1]. In this method, the transducer is rotated on its longitudinal axis (figure 1).

The acquisition of data was synchronized with the breathing rhythm and the heart rhythm; the manipulation of the ultrasonic transducer was carried out by a motorized servo-mechanism controlled by computer that allows the acquisition of sequences of 3D-images with a rotational and cylindrical symmetry.

Figure 1. Transtoracic rotational sampling, apical view. a) Position and movement of the transducer. b) two-dimensional echo obtained on the slice plane 1.


2.1. Front of Propagation 2D.

We can describe this model as the propagation of a closed curve, nonintersecting, with a speed that depends on the curvature. The basic curve begins to grow inside the image adapting and sticking to the walls of the structure or object to search. This technique can be applied with the purpose of looking for arbitrary shapes, which also include significant protuberances, and situations when an object's topology assumption cannot be carried out a priori.

It is possible to consider a propagation front like a curve moving in the plane. \( \gamma(0) \) is a smooth, continuous, derivable, closed and Euclidean curve, defined in the plane \( \mathbb{R}^2 \); and \( \gamma(t) \) are a family of curves generated by the movement of the interface \( \gamma(0) \) along their normal vector with a propagation speed \( F \).

The propagation of the front is defined by the evolution equation "\( \psi "\:

\[
\psi_t + F \nabla \psi = 0
\]  

Malladi & Sethian [2] have proposed several algorithms to solve the problem of the evolution equation. One of the algorithms that we have developed containing all these equations to programing the propagation front is the following:

1) Starting from an initial curve given by the user. The image of the 'distance' function is calculated.

2) The new "level set" function is calculated with the following equation:
\[
\Psi_{(x,y)}^{n+1} = \Psi_{(x,y)}^n + k_{(x,y)}^n \left( F_i^a(C_{i}^n) \right) \Delta t \left( \nabla V_{(x,y)}^n \Psi_{(x,y)}^n \right) \tag{2}
\]

The propagation front stops when the variable \( k_{(x,y)}^n \) approaches to zero.

\[
k_{(x,y)}^n = \frac{1}{\left| \nabla G_n \ast I(x,y) \right|} \tag{3}
\]

\[
F_i^a(C_{i}^n) = 1 - 0.25C_{i}^n \tag{4}
\]

The variable \( C_{i}^n \), is the curvature. The gradient is:

\[
\left[ \nabla \Psi_{(x,y)}^n \right] = \frac{y_{i+1}^n - y_{i-1}^n}{(x_{i+1}^n - x_{i-1}^n/2)} + \frac{x_{i+1}^n - x_{i-1}^n}{(y_{i+1}^n - y_{i-1}^n/2)} \tag{5}
\]

3) The new function \( \Psi_{(x,y)}^{n+1} \) is obtained calculating the points of the curve that complete with:

\[
\psi(t = 0) = [\hat{s} / \hat{D}(\hat{s}, \Psi(t = 0)) = 0] \tag{6}
\]

that is to say simply the 'level set' equal to zero.

4) If the error between the curve and its next propagation is smaller than \( \varepsilon \) stops the algorithm. To replace 'n' by 'n+1' and return to step 1.

Concluded the segmentation, the parameters of position and orientation are calculated. That parameters are used to segment the next slice.

2.2. Front 3D as sphere.

The extension of the 3D propagation front was made. The first method for the calculation of the distance corresponds to compute the distance from a point centered in the volume. We made the propagation in radial form to the center of a sphere (see figure 2).

![Figure 2. (a) Visualization of the simplified 3D front Propagation. (b) Cloud of points obtained with the front.](image)

The propagation in radial form limits the geometric 3D shapes that it can be detected, since they should be convex where all point of the border of the figure should have a visible way at the center of the image.

2.3. Description of the hierarchy of models.

The new idea of this work is the hierarchical approach of geometric 3D figures to an internal organ of the human body, in this case the left ventricle. The available models to carry out this approach are: the sphere, a super ellipsoid, a superquadric, and a hybrid volumetric ventriculoid. model [3]. These models are adjusting to the object that we want to detect using a descending gradient method, until minimizing the error. Then the parameters of the model are obtained. These parameters will be used in the following model's initialization inside the hierarchy.

The implicit equations of the sphere and of the ellipsoid are very well-known and the equation of the superquadric is the following one:

\[
\left[ \frac{x}{a} \right]^2 + \left[ \frac{y}{b} \right]^2 + \left[ \frac{z}{c} \right]^2 \tag{7}
\]

A superquadric [4] is a model that maps from two-dimensional space \((u,v)\) to a three-dimensional Cartesian space, parametrically defined by the following vector 3D.

\[
S(u,v) = \begin{bmatrix} x(u,v) \\ y(u,v) \\ z(u,v) \end{bmatrix} = \begin{bmatrix} a \cos^e(u) \cos^f(v) \\ b \cos^e(u) \sin^f(v) \\ c \sin^e(u) \end{bmatrix} \tag{8}
\]

where: \(-\pi/2 \leq u \leq \pi/2\) and \(-\pi \leq v < \pi\)

The parameters \(u\) and \(v\) corresponds to the latitude and longitude angles, respectively, expressed in a system of spherical coordinated centered in the object [5,6]. The scale parameters: \(a\), \(b\) and \(c\) define the size of the superquadric in the \(x\), \(y\), \(z\) coordinates, respectively. The exponents \(e_1\) and \(e_2\) produce an effect of squareness of the ellipsoid.

Following the hierarchy of the models, the “Hybrid Volumetric Ventriculoid” HVV [3] is an extension of the superquadric model. In this new model the parameters \(a\), \(b\) and \(c\), are functions that depend of two variables which represent the shape and the width of the internal and external walls defined on a half of a solid superquadric.

The hierarchical structure is the following: it begins with a very simple model as the sphere, until arriving to a complex model as a structure Free Form Deformation FFD. All the models are parametric, therefore inside of this structure we can pass among the sphere, ellipsoid, superquadric and superquadratic group, minimizing an implicit function, because this function can separate the 3D space in three regions: inside, outside, and over. These family of curves guarantee the convergence using the method of descending gradient.

![Figure 3. Structure of hierarchical evolution. a) Sphere. b) Ellipsoid whose main axes are: \((a,b,c) = (1,1,2)\). c) Superquadric with deformations: the main axes are: \((a,b,c) = (1,1,2)\). Twisting \(\theta = 20^\circ\). Tapering \(C_v = 0.3\). \(C_s = 0.3\). d) The “HVV” model [3].](image)
3. Adjustment of the model.

3.1. Data used.

To verify the model's behavior, we use a 3-D sequence of actual cardiac data made up of 13 volumes acquired in a cardiac period. These data were obtained by the authors in previous works [1]. The figure 4(a) shows a volume of the sequence.

To acquire this sequence we used the method of transthoracic rotational sweep and for each time instant we make sixty (60) radial sections of the ventricle (Figure 4(b)). The automatic segmentation obtained with the methods described previously is stored in form of vectors that can be visualized like a cloud of points that you will be used for the later adjustment of the model.

Figure 4. Actual 3D cardiac data used. (b) Radial sections of the ventricle obtained during the acquisition.

3.2 Adjustment of the Model Parameters.

We minimized the energy of the error for the adjustment of the model's parameters using the method of descending gradient for several variables.

We defined as objective function to minimize the following error expression between the model and the data:

$$ Err(a_i) = \sum_{j} [1 - F(p_n \colon a_i)]^2 $$

where:
- $p_n$: are the points obtained from the segmentation of the ventricle.
- $a_i$: are the parameters of the model.
- $F(p_n \colon a_i)$ is the implicit equation of the superquadric (eq. 8) with all transformations, with a total of 13 parameters.

The function $F(p_n \colon a_i)$ takes the following values:

$$ F(p_n \colon a_i) = \begin{cases} 
1 & \text{if } p_n \text{ is over the superquadric surface} \\
>1 & \text{if } p_n \text{ is outside the superquadric} \\
<1 & \text{if } p_n \text{ is inside the superquadric}
\end{cases} $$

The gradient vector of the error function ($\vec{\partial}Err$) indicates the direction of growth of the objective function. Therefore, the $a_i$ parameters are modified in small increments in the opposed direction. The following adjustment is made, in an iterative form, to each one of the parameters:

$$ a_i^{k+1} = a_i^k - \lambda_i \frac{\partial}{\partial a_i} Err $$

(11)

All the parameters are adjusted simultaneously and the magnitude of the modification is determined by the constant of adjustment $\lambda_i$ that is chosen independently for each $a_i$ parameter.

The iterative adjustment is made until the error function $Err(a_i)$ of each of the $a_i$ parameters is smaller than an $\xi$ value previously established.

3.3. Results

Figure 5. Results obtained when adjusting an ellipsoid to the left ventricle. One sphere born inside of the left ventricle begins to grow and it becomes an ellipsoid that will fill the whole ventricle at the end.

Figure 6. Graphic of the error in function of the number of iterations. It observes the difference of the convergence among a sphere, an ellipsoid and a superquadric.

In the graph of the figure 6, its possible to observe as the line of convergence of the superquadric is a little quicker at the beginning, then the sphere has the best convergence because it doesn't have to adjust many parameters and finally the convergence of the sphere arrives to a limit while varying the parameters of the superquadric can obtain a model that approaches much more to the shape of the left ventricle.

4. Three-dimensional reconstruction

This work has been demonstrated that it is possible to reconstruct the LV starting from the 2D segmentation obtained with the method of propagation front. Two
methods were used to make the 3D triangulation of the LV. In the first case we follow the points in the same direction and spatial angles used in the acquisition method. On the other hand we can consider the results of the segmentation like a cloud of points in the space, very closed each point to the other; and we can use the Delaunay triangulation methods.

When we use the methodology described in the section 2.3 of this work we obtain geometric figures more or less regular where we know the parametric equations and the parameters associated with the model, therefore we can know the space localization of the points and the best triangulation applicable to each model.

When we finished the 3D reconstruction; the results should be visualized. We have developed two visualization methods: The volumetric visualization using our program VVM (“Volume-Model Visualization”); and the surface visualization using the VRML language. We obtain three-dimensional objects easily governable with any VRML software. The images obtained when analyze the first instant of time of a volumetric sequence of the left ventricle are the following:

Figure 7. (a) Reconstruction 3D of the meridians of the left ventricle. (b) and (c) 3D Visualization the endocardium of the LV.

In the figure 7(a), the right side is wider than the left side because the rotation axis of the transducer doesn't coincide with the central axis of the left ventricle. We observed the aorta in the superior part of the ventricle on figures 7(b and c).

Figure 8. (a) The wire view of the global model of the LV is observed. It corresponds to the segmentation approach of the LV with the superquadrics model. (b) The rendering of the model is observed.

5. Conclusions

The convergence of the 3D geometric shape used as model to a cloud of points is possible. That shapes should divide the three-dimensional space in three different regions: inside, outside, and over of the surface. This behavior outside - inside determines quickly in which region falls an arbitrary point. In this work, we tested the convergence of several 3D geometric shapes to the endocardium of the LV. Then its possible to model beginning of the simplest shape like a sphere, changing automatically by the ellipsoid, and the superquadric. The descending gradient method does not converge in the case of the HVV model because it does not fulfill the previous conditions.

The relationships between the geometry of the Acquisition, the Segmentation and the modeling are very important to make the visualization and triangulation of the LV-surface. That is the only form to solve the problems of connectivity of points with the purpose to visualize the correct object.

The obtained results of the computing of the LV volume demonstrate that a model has evolved until arriving to a superquadric with a 1% of error. Therefore, we can conclude: the superquadric captures the global parameters of the LV. The doctors could manipulate and visualize the model easier than the volumetric data. Certain cardiac pathologies could be detected observing the dynamic and behavior of the model at global or local level.

References

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