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Clustering Based 3D Level Set Method for Volumetric Cardiac Segmentation

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Abstract: Multi-slice CT (MSCT) provides dynamic three-dimensional (3D) volumetric data of the whole heart, and is an important medical imaging tool for diagnosis of cardiac diseases. Due to the large size of the dynamic data, manual identification, segmentation and tracking of various parts of the heart will be very labor intensive and inefficient. Alternatively, sophisticated image processing techniques, which require minimal user intervention, can be developed and employed to automate such tasks. In this work, we propose a semi-automatic clustering based 3D level set method to robustly segment the endocardium surface from cardiac MSCT images. The theory of level set defines a flexible and powerful surface which is capable of capturing the complex endocardium anatomical structure. A novel speed function for the level set method using a clustering algorithm is proposed to exploit the non-homogeneous blood pool intensity property by supporting a set of independent intensity samples. To define the intensity clusters for the blood pool region and the surrounding region, only a few lines drawn on the corresponding regions are required as user input. The segmentation result is a level set 3D surface in the whole volume space which can readily be constructed to form a spatial model. Our clustering based 3D level set method can also be used for segmenting other heart wall surfaces by performing appropriate initialization. By extending to a 4D level set method, 4D (3D plus time) dynamic volumetric data could be readily processed

Introduction

To study the healthiness of the heart, various objective measurements might be required, such as ejection fraction, ventricle blood volume, wall mass, wall motion and wall thickness over various phases of the cardiac cycle. Accurate and robust heart wall, especially endocardium surface, segmentation is one of the most vital and challenging steps to determine these measurements. Endocardium has a relatively complex anatomical structure with various papillary muscles connecting between the heart wall and the valves. Traditional 2D or 3D active contour methods are often not effective nor sufficient in modeling such a complicated sharp concave surface. On the other hand, the non-homogeneous distribution of contrast inside the blood pool of the heart chambers can lead to significant segmentation error if only a predefined range of intensity value approach is employed.

In this work, we propose a semi-automatic clustering based 3D level set method to robustly segment the endocardium surface from cardiac MSCT images. The theory of level set defines a flexible and powerful surface which is capable of capturing the complex endocardium anatomical structure. A novel speed function for the level set method using a clustering algorithm is proposed to exploit the non-homogeneous blood pool intensity property by supporting a set of independent intensity samples.

We aim to segment the important cardiac structures, including the heart chambers, endocardium, myocardium, epicardium, coronary arterial vasculature, and valves, by performing appropriate clustering initialization. By extending to a 4D level set method, dynamic volumetric data of various heart regions could be readily identified, segmented, and tracked, which allows the determination of important cardiac measurements for medical diagnosis.

Materials and Methods

Segmentation of anatomical structures in medical imaging is an important and challenging task. The solution to this problem is not trivial due to the existence of the noise, complex region structure, and weak edges. Paragios proposed a shape-driven segmentation method for the left ventricle based on a prior shape assumption and a

simplified shape model [1]. In the myocardial SPECT segmentation algorithm proposed by Debreuve et al. [2], an energy function of the level set equation was minimized by assuming a constant intensity approximation of the object and background regions. In our medical application, however, the endocardium has a complex surface and non-homogeneous intensity values for the blood pool region and surrounding regions. Employing a simplified shape model and a constant intensity approximation will obviously be not suitable. We propose to use the level set method [3] together with a novel clustering based speed function to extract the endocardium surface. Comparing with other active contour approaches, level set is good at segmenting complex surfaces as the moving interface in level set can merge, split or even disappear. Clusters of intensity values provide a better representation of the non-homogeneous blood pool region and surrounding anatomical structures. A semi-automatic clustering based 3D level set method is developed to segment the region of interest, the endocardium in our case.

In a typical cardiac MSCT scan, the dynamic volumetric data size is large and might consist of 10 volumes of around 300 512×512 grayscale CT images for each heart cycle. If we use a 2D level set, an initial 2D contour has to be set in every slide of the volumetric data. In our 3D level set method, only one initial contour in one of the slides is required, and the contour will propagate to other slides and thus form a surface.

The level set theory was explained in details by Sethian in [3]. The main idea is to track the motion of the interface as it evolves. Let the moving interface be $\Gamma(t)$ t $\in$ [0, 1]. The level set function is set as

$$\phi(x, y, z) = \pm d,$$

where d is the distance between the point $p(x, y, z)$ and $\Gamma(t)$, and the plus/minus sign is chosen depending on whether the point is outside/ inside the interface. For points on the interface, we have

$$\phi(x, y, z) = 0, \quad (1)$$

Applying chain rule to (1) gives

$$\phi_t + F \mid \Delta\phi \mid = 0, \quad (2)$$

where F is the speed of the interface point along the normal direction. At any time the evolving interface is given by

$$\Gamma(t) = \{ p \mid \phi(x, y, z) = 0 \}.$$

Before the level set iteration, some input information from user is required. In our method, we need to sample intensities of the blood pool and surrounding regions, and the information of the initial surface. Our implementation allows users to perform the initialization by drawing a few curves on one slide of a volume dataset (see fig. 1). These curves include one closed curve for initializing the surface and several separate curves for the intensity clustering. The closed curve represents the initial 2D contour. The dark long dashed curve provides sample intensities of the blood pool and the white curve provides sample intensities of the surrounding regions.

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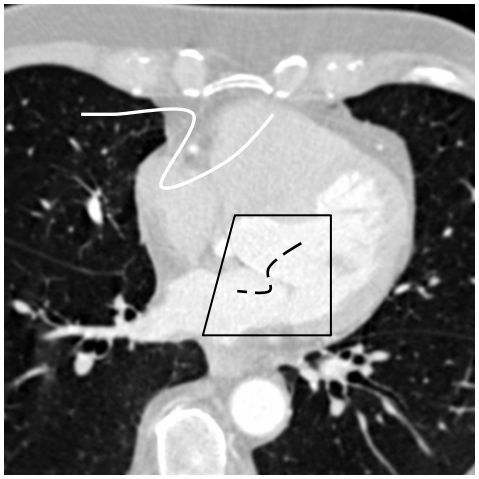

Figure 1: One closed curve for initialization and several separate curves for the intensity clustering. The closed curve represents the initial 2D contour. The dark long dashed curve provides sample intensities of the blood pool and the white curve provides sample intensities of the surrounding regions.

Next, we need to construct an initial surface for the level set function from the simple initial contour. The initial 2D contour is extended to a 3D box by adding two auxiliary neighbour surfaces. The clusters for background and endocardium are constructed from the intensity samples using the K-Mean algorithm [4]. The intensities of the clusters K_{io} and K_{ib} are obtained for the foreground and the background, respectively, where i $\in$ [0, n] and n is the number of the clusters.

In our method, we use a fast level set implementation which was proposed in [5]. This implementation has the advantage that the surface can be moved by simply switching elements between two linked lists. The level set surface evolves with the iterations. Finally, the level set surface stops and the segmentation result is computed.

The speed function F controls the deformation of the interface and is the most import part of the level set method. To segment the non-homogeneous structure, a clustering speed function is introduced in this paper. It is defined as

$$F = F_d + F_s,$$

where F_d is related to the clusters, and F_s controls the smoothness of the surface.

For every point *p(x, y, z)* on the volume space, the distance from its intensity to the foreground clusters is defined as d_o:

$$d_o = \min_{i \in [0,n]} \| I(x, y, z) - K_{io} \|$$

The distance from its intensity to the background clusters is defined as*:*

$$d_b = \min_{i \in [0,n]} \| I(x, y, z) - K_{ib} \|$$

The term F_d is then defined as:

$$F_d = \begin{cases} 0 & \text{if } p \text{ is a border point and } -\varepsilon \log(\frac{d_o}{d_b}) \geq 0. \\ -\varepsilon \log(\frac{d_o}{d_b}) & \text{otherwise.} \end{cases}$$

where ε is a positive constant.

F_d is designed to be positive when the point's intensity is near to the target clusters, and negative when it is near to the background clusters. Therefore, the level set surface can move from the initial slide inwards at the background and outwards at the target region. At last, the surface will stop and tightly surround the endocardium.

Results

To test our method, one timeframe of a dynamic volumetric data of cardiac MSCT was used. A contrast enhanced with saline tracer protocol was employed. The X-ray tube was set to 120kvp and the reconstructed resolution was 0.4mm by 0.4mm by 0.6mm. A standard smoothing kernel was used to produce smooth mediastinum. Endocardium segmentation results of three cardiac MSCT images using our proposed clustering based 3D level set method, are shown in Figure 2. Figure 3 shows multiple views of segmented endocardium surface. Figure 4 shows two views showing the sharp concave endocardium surface (pointed by arrows).

Discussion

The rough surface of the left ventricle can be visualized clearly from Figure 2, Figure 3 and Figure 4. In Figure 2, it shows clearly that both the endocardium and the background region have non-homogeneous distribution of contrast. In particular, Figure 4 shows that we are able to segment the concave surface part (pointed by arrows) which is caused by papillary muscle. It can be observed that the proposed semi-automatic clustering based 3D level set method can successfully segment the endocardium surface of the left ventricle.

Our segmentation method has integrated the advantages of 3D level set theory and clustering algorithm which have the capability to segment the complex endocardium surface with extending papillary muscles and to handle the non-homogenous CT number of blood pool region and the surrounding region in the cardiac MSCT images.

Conclusions

In this paper, we present a novel clustering based 3D level set method for endocardium segmentation from cardiac MSCT images. A novel speed function which exploits region cluster information is introduced. Combining such a speed function into the 3D level set method; the complex endocardium surface with sharp concave structure can be robustly segmented. The algorithm is readily extendable to handle multiple cardiac anatomical structures and dynamic volumetric dataset.

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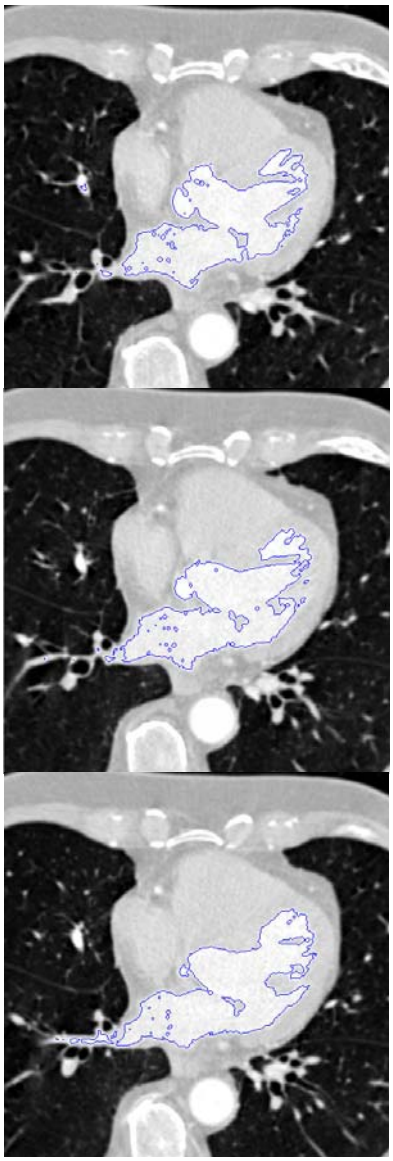

Figure 2: Endocardium segmentation results of three cardiac MSCT images using our proposed clustering based 3D level set method.

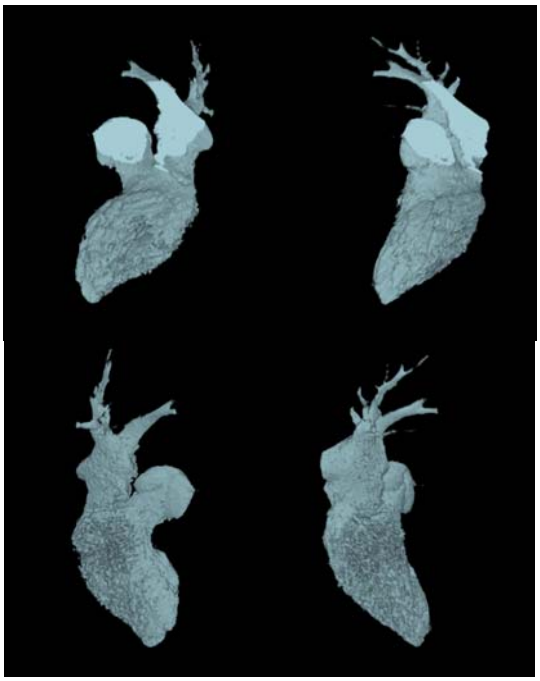

Figure 3: Multiple views of the segmented endocardium surface.

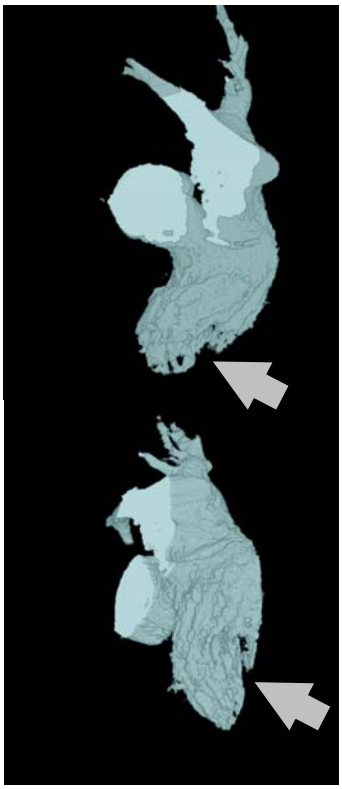

Figure 4: Two views showing the sharp concave endocardium surface (pointed by arrows) caused by papillary muscle (section of segmentation result is display)