Spatially Controllable Region Growing for Segmenting Heart Chambers

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Abstract  Segmentation of computed tomography (CT) images has provided promising methods of constructing precise 3-dimensional heart models. However, the process is labor intensive, because heart regions such as cardiac chambers and blood vessels have similar intensities and exist within a small space. In this paper, we present a tool to efficiently segment cardiac chambers and blood vessels. We extend traditional region growing to be spatially controllable. A user places multiple seeds, each having a bounding area and a threshold, and our tool "grows" regions around each seed independently within its bounding area. To efficiently specify the bounding area, we propose two types of seeds (i.e., sphere and cylinder). We also provide a negative seed that generates fixed background to avoid over-extraction errors. We compared our tool with a traditional scissors tool and confirmed that ours significantly reduced the time required for a segmentation task. We also present segmentation results of CT images of hearts having congenital diseases to illustrate the feasibility of our tool.

Keywords: Volumetric image segmentation, region growing, 3D heart modeling.

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1. Introduction

Computer simulation is a key technique to understand functionalities of the heart. Many researchers have developed methods for simulating activation propagation, blood flow, deformation [1–3], and whole-heart functionalities [4, 5]. Computer visualization is also a crucial technique to support education and communication [6]. For instance, researchers have visualized cardiac shapes and motions with real-time simulation [7], an interactive deformation tool on touch-screen tablet [8], and a rubber like soft replica [9, 10]. For these advancements, precise 3-dimensional (3D) modeling of the heart is required.

The segmentation of volumetric images captured by X-ray computed tomography (CT) or magnetic resonance imaging has been a promising solution to obtain 3D models. However, previous segmentation approaches have difficulties dealing with cardiac chambers and large blood vessels connected to the chambers, because they have similar intensities in a contrast-enhanced CT image. Moreover, the parts are crammed into a small space and often contact one another across thin walls.

Figure 1 shows the segmentation results of traditional region growing, a popular segmentation method that gradually grows foreground based on user-specified growth rules (e.g., thresholds). Various extensions of region growing have been reported [11, 12]. However, these techniques apply single growth rules to entire images, which often cause under- or over-extraction errors. With looser thresholds, chambers and blood vessels can be accurately extracted, but adjacent chambers and vessels are often connected incorrectly (red arrows in Figure 1c). Using tighter thresholds, adjacent regions are separated, but their detailed structures are often lost (red arrows in Figure 1d).

In this paper, we present a novel tool to support efficient segmentation of cardiac chambers and the blood vessels connected to them. Our tool extends traditional region growing, allowing it to be spatially controllable. It allows a user to place multiple starting points of region growing, i.e., seeds. Each seed has a bounding area and a threshold. Our tool then grows the foreground region...
for each seed within its bounding area. We propose two types of seeds: sphere and cylinder. These will support flexible specifications of bounding areas. We also introduce a negative seed to grow the background region that becomes a barrier to avoid over-extraction errors.

To evaluate the usefulness of our tool, we compared it with a traditional scissor tool and confirmed that it significantly reduced the time and the number of manipulations for a specific segmentation task. To illustrate the feasibility of our tool, we provide multiple segmentation examples of CT images of hearts having congenital diseases. Our technical contributions are listed as follows:

- We present the concept of spatially controllable region growing and illustrate its feasibility by conducting a user study with segmentation results.
- We provide two types of seeds for efficiently specifying bounding areas.
- We provide a negative seed for placing a background to avoid over-extraction errors.

2. Previous Works

Image segmentation is an active research field, and various algorithms have been reported, including thresholding, k-means clustering, mean shift, active contours, graph cut, and others [13, 14]. This paper focuses on interactive 3D segmentation techniques, which can be roughly classified into three groups based on user interfaces: painting, rough inside and outside specification, and boundary specification.

Painting. This group allows a user to paint the foreground manually. The most naive approach in this group is slice-by-slice painting, in which the user paints a region of interest (ROI) on each slice, one by one. To make this process more efficient, some researchers have developed semi-automatic tools. For instance, the intelligent scissors system automatically traces image edges [15]. The smart paint system [16] automatically adjusts effective areas of a paint brush based on local image features. However, these methods are quite labor intensive, because they require the users to paint many slices sequentially.

Alternatively, Igarashi et al. [17] introduced a more direct tool for painting the surface of an ROI. This method introduces spatially varying threshold fields. The user then modifies them via painting operations. This method significantly reduces the number of mouse and camera control operations. However, it was designed mainly for blood vessels in the brain, and it is difficult to deal with highly occluded structures such as cardiac chambers.

Rough inside and outside specification. To support efficient segmentation, several tools allow users to roughly specify inside and outside voxels. One example of this group is the traditional region growing, in which the user specifies several seeds in a 3D space with thresholds (or other growth rules). The seeded voxels are then used as the initial foreground, and the tool gradually grows the foreground by adding voxels that contact the current foreground and satisfy the threshold. This method has been extended to grow multiple regions simultaneously [11] or to adopt cellular automaton [12]. However, these methods apply the same growth rules for entire images, and the results are locally uncontrollable. This makes it difficult for users to correct local segmentation errors.

Boykov et al. [18] presented graph-cut segmentation, in which the user specifies inside and outside voxels. This method formulates segmentation as an energy minimization problem and solves it by adopting a max-flow algorithm. Yuan et al. [19] allowed the user to specify constraints directly on rendered images. However, the energy functions of these methods were designed for rounded organs, and are not well-suited for thin organs such as vessels and membranes.
Boundary specification. To extract an ambiguous ROI, some tools allow users to specify boundary constraints. The goal of this group is to generate a boundary surface from user-specified boundary curves. Various surface reconstruction approaches have been adopted for this purpose, such as explicit surface reconstruction [20], implicit surface reconstruction [21], and implicit surface reconstruction in a spatial range–joint domain [22]. However, these contour-based methods were also designed for rounded organs.

3. Methods

3.1 Region Growing with Bounding Areas

In this paper, we present a spatially controllable region-growing tool that extends traditional region growing such that the user can specify bounding areas. Ideally, our tool will satisfy the following requirements:

- the bounding area can be specified efficiently with a small number of operations, and
- the bounding area will have a similar shape to the ROI.

To strike a balance between specification efficiency and shape similarity, we combine multiple primitives. We allow users to place multiple seeds with their own bounding areas using primitive shapes. Although placing a primitive shape in a 3D space requires a few mouse operations, it is possible to specify the complicated shapes by combining multiple primitives. Given multiple seeds, we grow the foreground region for each seed independently, and the union of their foregrounds is thus returned.

3.2 Seed Types

To support flexible bounding area specifications, we provide sphere and cylinder seeds. The sphere seed has a sphere-shaped bounding area, and the user specifies its center position and radius (Figure 2ab). The cylinder seed has a curved cylinder-shaped bounding area, and the user specifies the axis polyline and radius (Figure 2cd). Because organs often have rounded shapes, and vessels are curved lines, the user can construct bounding areas that approximate the shapes of target organs and vessels by combining multiple seeds. By specifying multiple seeds and tuning their thresholds, it is possible to accomplish region growing using locally adaptive thresholds (Figure 2e–g).

Common issues related to traditional region growing include unintentional over-segmentation, in which the foreground extrudes the desired ROI (Figure 3a). It is more convenient if the user can explicitly control such extrusion. We therefore provide a negative seed to grow a background prior to growing other foreground seeds. Figure 3 shows the typical application of a negative seed. With simple region growing, the left atrium (LA) and pulmonary artery (PA) regions are incorrectly connected. This error is difficult to avoid using only sphere and cylinder seeds. With our tool, the user can place negative seeds to block the connection. The tool first grows the background region (Figure 3bc), and then grows the foreground (Figure 3d). As a result, incorrect over-extraction is avoided. The negative seed is also useful for stopping growths along specific blood vessels (Figure 3e–g).

3.3 Implementation

In this paper, we adopt simple thresholding to grow each
seed. In each iteration step, we add voxels that are adjacent to the current foreground region and satisfy:

\[ T_{\text{min}} \leq I(p) \leq T_{\text{max}}, \quad \text{and} \quad \text{dist}(p) < r, \]  

(1)

where \( I(p) \) is an image value at voxel \( p \), \( T_{\text{min}} \) and \( T_{\text{max}} \) are user-specified minimum and maximum thresholds, respectively, \( \text{dist}(p) \) is the distance of \( p \) from seed center, and \( r \) is the seed radius. The distance from the seed center, \( \text{dist}(p) \), is defined based on seed type. For the sphere seed, \( \text{dist}(p) \) is the distance from the voxel, \( p \), to the sphere center. For the cylinder seed, \( \text{dist}(p) \) is the distance from \( p \) to the cylinder axis polyline.

Computing the distance from a point to a polyline is time consuming if the polyline comprises many vertices. To solve this issue, we adopt a distance transform approximation [23]. We set the distance values of the voxels lying under the polyline to 0. We then compute the distance transform and use it as \( \text{dist}(p) \). The distance transform is used to determine whether a voxel is inside or outside the bounding area. Therefore, it is not necessary to compute distance field farther than the seed’s radius.

Note that simple thresholding has been employed to achieve the intuitive parameter tuning of our tool. Other growth rules [14] are available.

3.4 User Interface

Our tool is implemented on RoiPainter3D which is an open-source software for volume visualization and segmentation. The author’s web page [24] shows more detailed usage and source code. Figure 4 shows a screenshot of our tool that comprises a main window and two dialogs. The main window (A) provides volume rendering and planar cross sections. Dialogs (B, C) are used to modify parameters.

Figure 5 shows the user interface. The user starts by moving the planar cross sections using the mouse wheel, so that the target ROI is well-visualized (a). A sphere seed is placed by left-button double-clicking on the plane (b). If the user does this multiple times (d), vertices are added to generate a cylinder seed (e). If the user performs right-button double-clicking in a similar manner, negative sphere/cylinder seeds can be placed (g). The dialog lists all the existing seeds (Figure 4C), and the user can activate them by choosing from the list. At any time, the user can activate an existing seed and modify its threshold and radius using the dialog. Moreover, the user can move/delete an existing seed by dragging/double-clicking. If the user presses the "run segmentation" button from the dialog, it computes the segmentation and visualizes the results (c, f, i). A segmentation result is usually computed in several seconds.

4. Results and Discussion

To quantitatively evaluate the usability of our tool, we compared it with a traditional scissor tool. To illustrate the feasibility of our tool, we also provided the segmentation results of 3D contrast-enhanced CT images. All CT images used in this study were taken following appropriate informed consent procedure at National Cerebral and Cardiovascular Center (NCVC).

4.1 Comparison with the Scissor Tool

We conducted a user study that compared our tool with the traditional scissor tool. The scissor tool is a popular tool that supports removal of parts of an ROI. The user draws a scissor stroke on a rendering screen, and the voxels in the stroke are removed (Figure 6ab).

We compared our tool with the scissor tool for a task to segment an LV and an aorta from a contrast-enhanced CT image. In general, this task is labor intensive, because the LV and aorta are surrounded by regions with similar intensities. A scissor tool is commonly used for this task. First, one extracts the ROI with surrounding region via region growing (Figure 6c) and removes the...
surrounding region by drawing multiple scissor strokes (Figure 6d). Our tool is also useful for this task, because it computes region growing only in seeds (Figure 6ef).

4.1.1 Tasks of the User Study

The user study comprised a practice step for learning the usage of the tools and a task step for measuring performance. In both steps, the user segmented the LV and aorta (we call ROI) from a CT image using our tool and the scissor tool. The order of the tools was balanced among the participants. Prior to segmentation, we presented a target CT image and its ROI, asking the participants to browse them freely for a few minutes. We also provided a printed image of the target ROI for the participants to check at any time. During the task, participants were able to ask questions about the tools and CT images.

Practice step. After explaining the basic RoiPainter3D manipulations, we showed a target CT image and its ROI for a few minutes. We then explained the usage of our tool and asked participants to segment the ROI with our tool. We also explained the usage of the scissor tool and asked the users to segment the ROI. Segmentation using the scissor tool began with an initial ROI generated by region growing, as in Figure 6c. A practice step with our tool and the scissor tool took about 15 min each.

To support efficient practice, we showed the participants four typical seed-placement examples (Figure 7a) and four typical scissor-stroke examples (Figure 7b). At the beginning of each task, we asked participants to place seeds or draw scissor strokes following the examples. Then, they were allowed to freely perform segmentations.

Task step. During the task step, participants segmented the same ROI from a different CT image. After browsing a target CT and the ROI for a few minutes, the participants segmented the ROI twice using our tool and the scissor tool. We asked them to perform the segmentation as quickly and accurately as possible. When using our tool, we provided the threshold parameter to the participants, because our focus was on the usability of seed placement. The scissor tool task began with an initial ROI that was generated by standard region growing with the same threshold provided in our tool.

4.1.2 Segmentation Results of Participants

Seven undergraduate students from the departments of computer science and engineering participated in the user study. None had experience with 3D segmentation.

Times and numbers of manipulations. We summarize the time to finish segmentation tasks in Figure 8a. The average time with our tool was 337.0 s, and that with the scissor tool was 572.7 s. For all participants, the time to finish segmentation with our tool was shorter than that with the scissor tool. A significant difference ($p < 0.01$) between these average times was found in a one-sided paired $t$-test. We also counted the number of mouse manipulations, including clicking, dragging, and wheeling. Figure 8b summarizes the number of mouse manipulations. All participants completed their segmentations using our tool with fewer operations than the scissor tool. The average number of manipulations with our tool was 139.4, and that of the scissor tool was 257.0. A significant difference ($p < 0.05$) between these average numbers was confirmed in a one-sided paired $t$-test.

Our tool significantly reduced the time and the num-
number of mouse manipulations compared with the scissor tool. This reduction was due to the differences in the number of seeds required by our tool and the number of strokes required of the scissor tool. Participants completed the tasks by placing 5.0 seeds and 19.3 vertices on average. Note that a cylinder seed comprised multiple vertices. In contrast, the scissor tool required many more strokes. The participants drew 76.6 strokes on average.

Segmentation accuracy. In the segmentation results obtained using our tool, we found common errors, in which parts of the ROIs were missing. Figure 9b shows a representative example with missing LV parts. Such errors occurred when the seeds did not cover the ROI. We found this error in five of seven participants. Using the scissor tool, we found common errors, in which parts of ROIs were incorrectly cut out. Figure 9c shows a representative example, in which a part of the aorta was cut. This error occurred when a scissor stroke intersected the ROI, and the user did not notice it. Although some were very small, we confirmed this type of error in nearly all participants.

These errors remained, because we did not instruct participants to check the results of all slices at the ends of their tasks. Note that the errors caused by our tool can be corrected easily by placing a few additional seeds at the missing areas. In contrast, it is difficult to correct the errors caused by the scissor tool, because the user is required to undo many strokes to find the one that causes the error.

4.2 Segmentation Results of Cardiac Chambers

Figure 10 presents the segmentation results of our tool for three different hearts having congenital disease. The inputs were contrast-enhanced CT images: data_A, data_B, and data_C (Figure 10a–c). We extracted all four chambers and blood vessels connected to the chambers. We first placed a sphere seed having a tight threshold at the center of the heart to obtain its overall shape. We then added multiple small sphere seeds having loose thresholds to extract thin vessels. Then, we placed small negative seeds to avoid over-extraction. For data A, B, and C, the segmentation was performed in less than 30 min. The number of seeds used for segmentation is summarized in Figure 10.

Figure 10d shows another segmentation result. In this example, we extracted the LV and aorta. We placed cylinder seeds in the aorta and a sphere seed in the LV. The concept of bounding area control achieved such selective segmentation in the region-growing framework. Figure 10e illustrates the usefulness of the negative seeds. In this example, one positive seed was used to extract the chamber region. However, the LA and RA were inaccurately connected. The user then placed a negative cylinder seed to block the connection. Note that such connection cannot be avoided when using the scissor tool, because it is difficult to draw a scissor stroke when the target parts are occluded by other regions. Figure 10f indicates the feasibility of our spatially controllable region growing. Thin vessels usually have low intensities, and it is thus difficult to extract them correctly. Our tool allows the user to place a seed having a small bonding
area and a low threshold, resulting in the desired segmentation.

5. Conclusion

In this study, we propose a spatially controllable region growing technique for segmenting cardiac chambers and blood vessels. Our key concept is to introduce a bounding area for each seed to limit region growing within the area. To support flexible bounding area specifications, we propose sphere and cylinder seeds. We also use negative seed to generate background region to avoid over segmentation. We performed a comparison between our tool and the traditional scissor tool and confirmed that our tool significantly reduced the time required for a specific segmentation task. We also present multiple segmentation results of hearts having congenital diseases to indicate the feasibility of our tool.

A limitation of our tool is that it is labor intensive to specify complicated bounding areas. It is thus necessary to introduce more flexible bounding area specification tools such as freeform surface seeds, and to automate their placement. Another future work is to apply our tool to other organs.

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References

1. Lin DHS, Yin FCP: A multiaxial constitutive law for mammalian left ventricular myocardium in steady state barium contracture of tetanus. J Biomech Eng. 120(4), 505–517, 1998.
2. Feng L, Weixue L, Ling X, Guohua W: The construction of three-dimensional composite finite element mechanical model of human left ventricle. JSME Int J Ser C Mech Syst Mach Elem Manuf. 44(1), 125–133, 2001.
3. Amano A, Kanada K, Shibayama T, Kamei Y, Matsuda T: Model generation interface for simulation of left ventricular motion. In Proc Eng Med Biol Soc. 5, 3658–3661, 2004.
4. Watanabe H, Hisada T, Sugiuira S, Okada J, Fukunari H: Computer simulation of blood flow, left ventricular wall motion and their interrelationship by fluid-structure interaction finite element method. JSME Int J Ser C Mech Syst Mach Elem Manuf. 45(4), 1003–1012, 2002.
5. Sugiuira S, Washio T, Hatano A, Okada J, Watanabe H, Hisada T: Multi-scale simulations of cardiac electrophysiology and mechanics using the University of Tokyo heart simulator. Prog Biophys Mol Biol. 110(2), 380–389, 2012.
6. Haraguchi R, Nakao M, Kurosaki K, Iwata M, Nakazawa K, Kagisaki K, Shiraishi I: Heart modeling of congenital heart disease based on neonatal echocardiographic images. Adv Biomed Eng. 3, 86–93, 2014.
7. Ijiri T, Ashihara T, Umetani N, Igarashi T, Haraguchi R, Yokota H, Nakazawa K: A kinematic approach for efficient and robust simulation of the cardiac beating motion. PLoS ONE. 7(5), journal.pone.0036706, 2012.
8. Nakashima K, Koyama Y, Igarashi T, Ijiri T, Inada S, Nakazawa K: Interactive deformation of structurally complex heart models constructed from medical images. Eurographics. 2016, Short Papers, 2016.
9. Shiraishi I, Yamagishi M, Hamaoka K, Fukazawa M, Yagihara T: Simulative operation on congenital heart disease using rubber-like urethane stereolithographic biomodels based on 3D datasets of multislice computed tomography. Eur J Cardiothorac Surg. 37(2), 302–306, 2010.
10. Fujita T, Fukushima S, Fukushima N, Shiraishi I, Kobayashi J: Three-dimensional replica of corrected transposition of the great arteries for successful heart transplantation. J Artif Organs. 20(3), 289–297, 2017.
11. Adams R, Bischof L: Seeded region growing. IEEE PAMI. 16(6), 641–647, 1994.
12. Vezhnevets V, Konouchine V: “GrowCut” - interactive multi-

Fig. 10 Examples of segmentation of hearts with congenital diseases.
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