DYNAMIC GRAPH CUTS FOR COLON SEGMENTATION IN FUNCTIONAL CINE-MRI

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ABSTRACT

A major limitation of graph cuts for the segmentation of large 2D image sequences is its interactive nature. The user has to provide seeds for almost every image frame to get an accurate segmentation. Straightforward approaches like direct copying of seeds provided in the first frame to other frames of the sequence fail in cases of great contrast or topological changes that occur when there is a large temporal distance between frames. In this work, we propose a dynamic seed propagation technique which can automatically adjust to any contrast or topological changes in a sequence. To this end, distance transform and skeleton extraction methods are employed to initialize the segmentation of the current frame using the result of the previous one. The proposed methods were used for the segmentation of functional cine-MRI sequences of colon which is especially challenging due to the large temporal distance between its frames. Both quantitative and qualitative results show good performance of the proposed method.

Index Terms— Graph cuts, cine-MRI, segmentation, colon

1. INTRODUCTION

Functional gastrointestinal disorders, to name the most common diarrhea, chronic constipation, irritable bowel syndrome and pseudo-obstruction, are conditions presenting with a significant socioeconomic burden. Chronic constipation is one of the most common of these conditions which is one of the leading diagnoses for gastrointestinal (GI) disorders in the United States [1]. One important type of constipation is the slow-transit constipation associated with slow colonic transit time which is usually attributed to colonic motility disorders [2]. Therefore, it is necessary to study colonic motility in order to understand its effects on such conditions leading to an improved and more adequate therapy in the end.

Existing well-established examination techniques such as manometry or scintigraphy are either invasive and inconvenient or expose patients to ionizing radiation creating the demand for a fast and non-invasive monitoring technique for the evaluation and quantification of colonic motility. On the other hand, functional cine magnetic resonance imaging (cine-MRI) allows for non-invasive, fast dynamic imaging with a superb soft tissue contrast [3].

The first use of cine-MRI for the analysis of colon motility was reported in [4] where luminal diameter changes were considered as a motility parameter and manual diameter measurements were performed in the ascending, transverse and descending parts of the colon. Sets of 2D dynamic image sequences from the same imaging plane over time were acquired using a T2-weighted single shot HASTE sequence. Due to the respiratory gating the sampling in time was irregular, therefore, a continuous tracking of lumen diameters was not feasible. Glocker et al. [5] extended this approach by addressing the irregular sampling in time and manual measurements on each 2D frame. A semi-automatic tool was developed to perform automatic diameter measurements on the data acquired during free breathing. Prior to diameter measurements, the colon was segmented in 2D dynamic sequences using the graph cuts [6] approach where the user provides seeds for object and background in the first frame. Due to the inconvenience of placing seeds in each frame separately, the seeds on the first frame were directly propagated to the other frames of the sequence and a subsequent segmentation was performed by considering a 2D sequence as a volumetric image.

Although graph cuts provides globally optimal solutions, one needs to fine tune the region and boundary parameters for every segmentation. Despite the global motion compensation, the colonic contractions between successive frames might be large enough to leave the seeds from the first frame invalid leading to an inconsistent segmentation in the end. A possible solution to this is to update the seed points for every frame to be segmented by using the segmentation of the previous frame reducing the human interaction, thus bias. Such a dynamic seed placement procedure will provide more flexibility for the segmentation method to allow for large morphological differences of the colon over time.

Therefore, in this work, we propose the use of a dynamic seed placement procedure for the segmentation of 2D dynamic MR-image sequences where topological changes do not allow for direct use of the same seed brushes for subsequent frames.

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2. MATERIALS AND METHODS

2.1. Functional Cine-MRI Acquisition

Functional cine-MRI was acquired using a half Fourier acquisition single shot turbo spin echo sequence (HASTE; TR: 476 ms, TE: 54 ms, SL: 5 mm, FOV: 320 x 400 mm, i-Pat-factor: 3.0, voxel size: 1.25 x 1.25 x 5.0 mm, duration: 8 min). Three orientations oblique to each other were set, examining 1 slice per orientation (transversal, sagittal, coronal) with a time interval of 4 s between image-sets to be able to physiologically image bowel motility. For more details about the image acquisition protocol, we refer the reader to [7].

2.2. Dynamic Graph Cuts

2.2.1. Graph Cuts

The interactive graph cuts approach was proposed by Boykov and Jolly [6] and has since been used extensively in a multitude of applications. Let P be the set of pixels p in the image $I : \Omega \rightarrow \mathbb{R}, \Omega \subset \mathbb{Z}^2$, $\mathcal{N}$ set of neighboring pixel pairs (p, q) in P, $L = (L_1, \ldots, L_p, \ldots, L_{|P|})$ a label configuration for a binary segmentation where $L_p \in \{obj, bkg\}$, $G = (V, E)$ a graph with nodes, V, and edges, E, $\mathcal{S}_{obj}$ and $\mathcal{S}_{bkg}$ sets of pixels defined by the user for object and background, respectively. The label configuration, i.e. segmentation, can be formulated as an energy minimization problem

$$E(L) = R(L) + \lambda \cdot B(L) \tag{1}$$

which when minimized assigns image pixels into two subsets $\mathcal{O}$ (object) and $\mathcal{B}$ (background) where

$$L_{p\in\Omega} = \begin{cases} \text{“}obj\text{”} & \text{if } p \in \mathcal{O} \\ \text{“}bkg\text{”} & \text{if } p \in \mathcal{B}. \end{cases} \tag{2}$$

Here, the regional term R penalizes the labeling of the pixels based on the intensity models of object and background. The function R is defined as

$$R(L) = \sum_{p\in P} R_p(L_p) \tag{3}$$

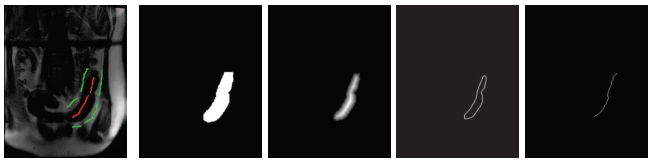
where

$$R_p(L_p) = -\log \Pr(I_p \mid L_p) \tag{4}$$

is the negative log-likelihood of object or background intensity distributions obtained from the user seeds. For the pixels the label of which are provided by the user, the regional term is defined as

$$R_p(L_p) = \begin{cases} \infty & \text{if } L_p = \text{“}obj\text{”} \wedge p \in \mathcal{S}_{bkg} \\ \infty & \text{if } L_p = \text{“}bkg\text{”} \wedge p \in \mathcal{S}_{obj} \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

The second part B of the segmentation energy is called the boundary term representing the energy for pairs of neighboring pixels $p, q \in \mathcal{N}$ to have to the same segmentation label. It



(a) (b) (c) (d) (e)

Fig. 1. (a) Seed brushes in one frame of the dynamic image sequence. (b) Resulting segmentation of the descending colon. (c) Distance map of the segmentation. (d) Extracted level curve. (e) Extracted centerline.

is defined as

$$B(L) = \sum_{p,q\in\mathcal{N}} B_{p,q} \cdot \delta(L_p, L_q) \tag{6}$$

where

$$\delta(L_p, L_q) = \begin{cases} 1 & \text{if } L_p \neq L_q \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

$B_{p,q}$ can be defined as a penalty function

$$B_{p,q} \propto exp(-\frac{(I_p - I_q)^2}{2\sigma^2}) \cdot \frac{1}{dist(p, q)} \tag{8}$$

which penalizes the dissimilar neighbors to have the same labels. The minimum of this functional can be computed by finding the minimum cut on the corresponding graph using efficient min-cut/max-flow algorithms [8].

2.2.2. Dynamic Seed Placement

The traditional graph cut segmentation algorithm proposed by Boykov and Jolly [6] is applicable to N-D data, including 3D medical image data and temporal volumes constructed from video frames. However, when the size of the data to be segmented gets larger, the segmentation becomes a difficult problem to solve and the performance turns out to be an issue. Furthermore, the large size of the data leads to an inconvenient interaction for the user. For the segmentation of volumetric images, one could initialize the segmentation on one of the slices and use the region properties, such as the intensity distribution, extracted from that slice for the entire volume since they are similar for the object in every slice of the volume. For live video sequences, the flow recycling approach [9] provides good initialization on a frame using the resulting flow from the previous cut. However, it is based on the assumption that changes between consecutive frames are *small*.

The above mentioned methods cannot be directly applied to our data sets where there are significant contrast changes between consecutive frames. Several factors, such as the dynamic nature of the abdominal region causing out-of-plane motion, fast imaging requirements for capturing colon motility which leads to low resolution and the low quality of images, require special treatment for cine-MRI sequences.

Due to the changes in regional properties for the object and the background between successive frames and topological changes throughout an image sequence, the hard constraints provided by the user have to be updated for every frame. It is inconvenient for the user to place seeds in every frame in a large sequence. Instead we propose an automatic initialization procedure by using centerline extraction and distance transform. For every frame to be segmented, we initialize the object seeds using the samples taken from the centerline and/or the level curves of the distance map. Given a binary image corresponding to the segmentation of the previous frame, we obtain the distance map using a distance transform $D(p) : \Omega \rightarrow \mathbb{R}$ defined as

$$D(p) := \begin{cases} min\left\{d(p,q)|q \in \mathcal{B}\right\} & \text{if } p \in \mathcal{O} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

where

$$d(p,q) = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2} \quad (10)$$

is the Euclidean distance. A level curve is extracted from the distance map by thresholding at a user defined level c. The centerline of the binary image is extracted using a thinning algorithm[10]. The level curve and the centerline are sampled equidistantly and these samples are used as object seeds for the next frame. We place the background seeds around the object making sure that they are placed in the surrounding tissue and that they never cross the object boundary throughout the whole sequence.

3. EXPERIMENTS AND RESULTS

Experiments have been conducted to demonstrate the effectiveness of the proposed method. A dynamic 2D coronal Cine-MRI sequence was used for the study. The sequence consists of 336 frames of size 256x320 pixels and presents significant contrast and topology changes. Four different initialization techniques were used for the segmentation of this sequence; a standard copy/paste (CP) technique where the seeds for the first frame are directly copied to every other frame, proposed dynamic seed placement techniques using skeleton (SKE) and level curve (LC), finally, a combination of skeleton and level curve extraction (SKE+LC). We set $c = max(D)/2$ for the level curve extraction.

User seeds are provided for the first frame as shown in Fig. 1(a). The background seeds are copied always from the first frame. Object seeds are updated depending on the chosen seed placement technique. Sample frames from the sequence are shown in Fig. 2 where the unsegmented frames are shown in the first column and the segmentation results overlayed on the original frames are shown in columns 2 to 5. Note that the region of interest (ROI) is defined by the user seeds. Therefore, only the descending part of the colon is segmented by placing the seeds only around this part of the colon.

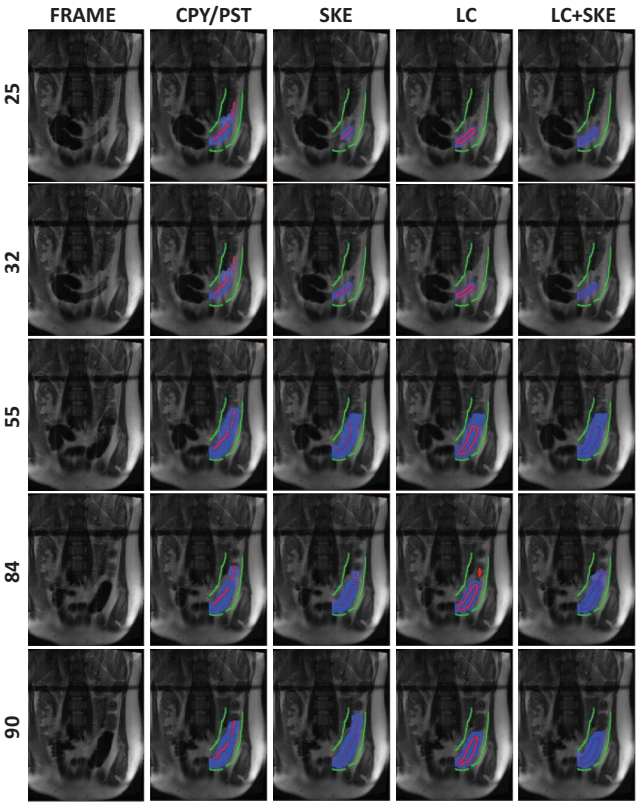


Fig. 2. Sample frames from the dynamic image sequence together with their segmentation results obtained by using different seed placement approaches. The flexible nature of the dynamic approaches is quite obvious especially for frame 25 where the colon shape is very different from the initial frame shown in Fig. 1(a). Note: Please refer to the electronic version of this paper to make full use of colors in this figure.

The results in Fig. 2 qualitatively demonstrate the poor performance of the copy/paste procedure based on the assumption that minor changes in terms of contrast and topology occur in the sequence. On the other hand, the results also reveal the good performance of dynamic seed placement techniques based on the previous segmentation and their flexibility during colon contractions leading to large topological changes. Dice coefficient was used for the quantitative evaluation of the results. Segmentation of each frame was compared to a ground truth where object seeds were placed manually on every frame. The Dice scores of each scenario for every frame in the sequence are plotted in Fig. 3. Dynamic seed placement based segmentations represent a higher consistency over time. The mean and the standard deviations (STD) of the Dice scores for each case are shown in Table 1. Dynamic techniques present not only with higher mean Dice scores but also with lower standard deviations throughout the sequence.

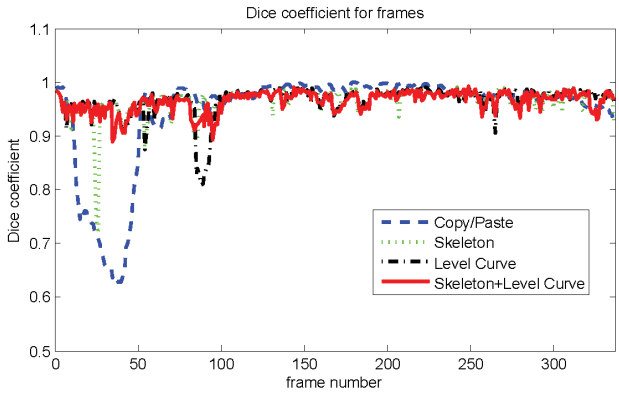


Fig. 3. Dice scores for every frame plotted against frame number using different seed placement approaches.

Statistics	CP	SKE	LC	SKE+LC
Dice Mean	0.946	0.966	0.966	0.964
Dice STD	0.088	0.027	0.029	0.019

Table 1. Mean and standard deviation of Dice scores for different seed placement approaches.

4. DISCUSSION AND CONCLUSION

In this paper, a dynamic seed placement technique for the semi-automatic segmentation of dynamic 2D Cine-MRI image sequences using graph cuts has been proposed. The qualitative and quantitative evaluation of the experimental results suggest that using dynamic seeds for the segmentation of abdominal Cine-MRI increases the robustness of the segmentation against intrinsic topological and contrast changes throughout the sequence.

Currently, only the object seeds are being updated. The background seeds have to placed on the first frame so that they never fall in the object region throughout the sequence. This requires a careful selection of neighboring tissues that remain stable over time. Although it is easy to find such regions in the ROI, a semi-automatic selection of background seeds would make intuitively more sense within the context of this paper. A straightforward approach would be the use of outer level curve from the signed distance function. However, this is not an easy task as in the case of inner level curve where the seeds always fall in the object region. During the distension of the colon, the extracted seeds might fall into the colon region in the current frame resulting in an erroneous segmentation. Extension of the dynamic placement approach to the background seeds is the subject of our current research.

5. REFERENCES

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