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Efficient block-wise temporally consistent contour extraction in image sequences

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ABSTRACT

In this paper we investigate the problem of temporally consistent consecutive contour extraction in image sequences, including both single and multiple boundaries. By formulating this problem in the form of an optimal surface detection in 3D volume, we are able to resort to a graph-theoretic approach for exact solution. In order to cope with the high computational complexity caused by the potential unboundedness in time (i.e., an image sequence can be arbitrarily long) and heavy noise, we propose three approximate block-wise variants to accelerate the solution process. The effectiveness and efficiency of our approach is exemplarily demonstrated on simulated data and real ultrasound data for arterial wall detection. It is shown that the approximate variants dramatically reduce the computation time without loss of solution quality.

1. Introduction

Contour extraction plays an important role in (biomedical) image analysis. Classical approaches include dynamic programming [1], snakes (active contours) [2], level set techniques [3], and minimum path approaches [4]. These and their improved variants [5–10], just to name a few, provide the foundation for many practical applications.

Recently, many improved contour detection algorithms have been proposed in the literature. For instance, dynamic programming is extended in [11] to a non-gradient based variant. In [12], local image feature is proposed to be embedded in the active contour model, which accelerates the convergence speed and avoids being trapped in the local minimum. An active contour model is introduced in [13], which is driven by local intensity and gradient energies. A further variant of energy can be found in [14] with local Gaussian distribution fitting energy. In [15], a decoupled active contour model is proposed, which decouples the traditional energy into two steps in order to incorporate a dynamic prior estimation. A new deformable model based approach is presented in [16], which can integrate constraints from multiple sources (edges, region information, statistical priors, and geometric/spatial priors). In [17], the minimum path method is extended towards more general dynamic propagation speed functions. Another extension is given in [18] to deal with unknown endpoints. An edge following technique is proposed in [19], which combines the information of edge vector field and edge map. Since contour detection in single images is not the focus of this work, we do not present a more detailed literature review, but refer the reader to these recent works and the references therein.

When segmenting contours in image sequences, the general method consists in applying some contour detection algorithms to each image separately, e.g. [20,21]. But this independent handling of temporally correlated images may result in temporally inconsistent segmentation results. As an illustration, Fig. 1 shows the arteria extraction results of using dynamic programming [6] in adjacent images. The extraction result in (a) is correct, while the result in (b) is obviously drifted, caused by the noisy pixels marked in the red ellipse in (c).

Sequence data generally require temporal consistency of segmentation results. In medical image analysis, for example, experienced physicians subconsciously follow the temporal consistency when they are asked to provide an expert ground truth segmentation of single images. In practice temporal consistency typically exists in sequence data. As an illustration, Fig. 2 shows the statistics of frame-to-frame differences in the y-direction of ground truth contours between two adjacent frames in an ultrasound sequence of 78 images. The vast majority of these differences is no more than two pixels. It is the temporal consistency that eases the manual segmentation of individual frames and should thus be expected from image sequence segmentation algorithms as well.

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A rather straightforward way of achieving temporally consistent segmentation is given by stacking all images from a sequence together to form a 3D volume, where the third dimension is time. Then, the original 2D consecutive contour segmentation problem is reformulated as the optimal surface segmentation problem (in terms of minimum cost) with temporal consistency constraints in 3D volume. Conceptually, this approach is equivalent to extending the minimum-cost 2D contour detection by highly efficient dynamic programming [1,5] to the 3D case. Unfortunately, there does not exist easy algorithmic extension of dynamic programming to 3D. The solution from [22] is a concatenation of two steps of 2-D dynamic programming. Dynamic programming is applied to each individual image first and then to virtual image planes spanned by the y-axis and the time axis (based on the result matrix from the first round). It is important to note that this efficient approach does not exactly solve the optimal surface detection problem, but delivers an approximate solution only. In addition, it cannot guarantee the temporal consistency. Fortunately, the graph-theoretic approach [23] provides an exact solution to this optimization problem and can thus be applied to solve the problem of temporally consistent contour extraction in an image sequence.

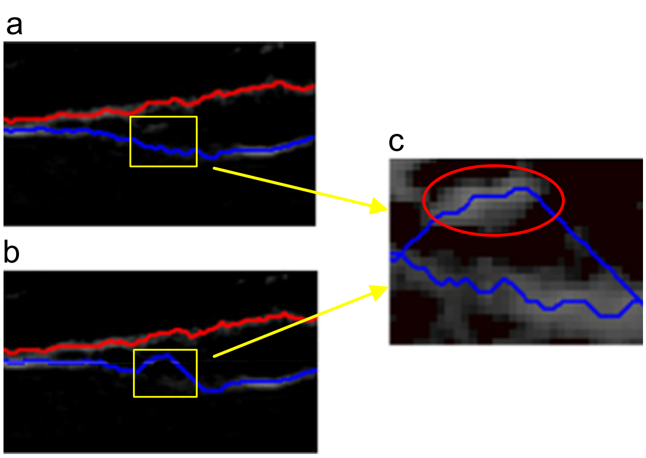

Fig. 1. (a) and (b) Contour extraction results in two adjacent frames. The noisy pixels marked in the red ellipse of (c), which is part of frame $i+1$, causes the inconsistent extraction along the time axis. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

The need of detecting temporally consistent contours in a global manner has also be recognized in [24]. However, the authors stated “Detecting boundaries in an image sequence can be viewed as detecting a surface in 3D-space. The problem is that, for dynamic programming, there exists no general extension to 3D that is guaranteed to find the optimal surface”. Obviously, they were not aware of the fact that the optimal surface detection algorithm from [23] is exactly a 3D extension of the 2D dynamic programming for contour detection (although being based on two different algorithmic paradigms).

In addition to the temporal consistency, the optimal surface search approach has another advantage of being able to deal with individual strongly distorted images within a sequence. Applying some contour detection algorithm to each frame separately will certainly have trouble with these images. The optimization scheme within the 3D volume will help “smooth out” such discontinuous data. This idea has been adopted, for instance in [22]. But the method based on dynamic programming in that paper can only deliver a suboptimal solution.

However, the graph search algorithm becomes computationally demanding for long image sequences. In particular, simultaneously detecting multiple contours leads to the problem of simultaneously detecting multiple surfaces in a 3D volume, which has a substantially increased computational complexity (see Section 3 for a complexity discussion). In practice, this algorithmic variant is highly required because of the numerous instances of multi-contour, or more specifically, multi-coupled contours (to be defined in Section 2) [5,25,26].

In this paper we study approximation schemes for the optimal surface detection algorithm from [23] in the context of temporally consistent contour extraction in image sequences in order to reduce the computation cost. Instead of processing all images in a 3D volume, the sequence is partitioned into blocks, each being processed by the algorithm from [23]. Three strategies are proposed to ensure smooth transition from one block to another to preserve the temporary consistency. The effectiveness and efficiency of our approach is demonstrated on two sources of data: simulated data and ultrasound image sequences (for arterial wall detection).

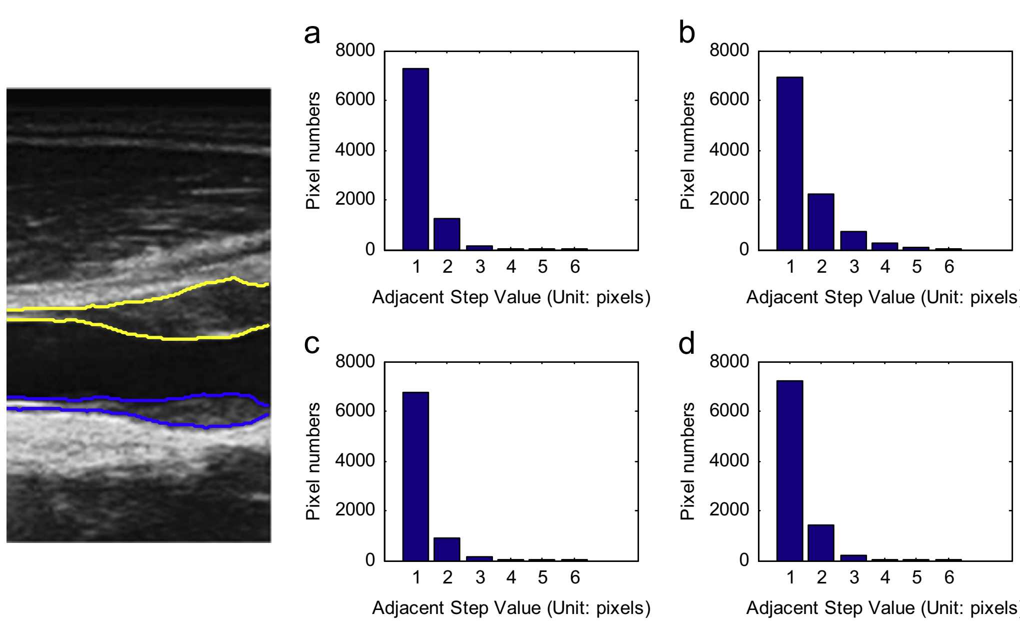

Fig. 2. Arterial walls labeled by experienced physician; statistics of frame-to-frame differences in y.