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A polynomial piecewise constant approximation method based on dual constraint relaxation for segmenting images with intensity inhomogeneity

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ABSTRACT

In the past decade, several local region-based level set models have been proposed to segment images with intensity inhomogeneity. In general, these models are designed based on one assumption, i.e. intensity inhomogeneity is slowly varying in image domain. However, this assumption is not valid for those images with serious intensity inhomogeneity, which inevitably leads to poor segmentation performance of existing models. In this paper, we propose a novel level set method named as polynomial piecewise constant approximation (PPCA) to well segment images with serious intensity inhomogeneity. The basic idea of the PPCA method is to transform the original image to piecewise constant image so as to make piecewise constant segmentation criterion become applicable. Specially, we firstly define an initial objective function with some constraint conditions to transform the original image. Then, in order to obtain desirable piecewise constant image and highlight the anti-noise performance, the PPCA method is used to realize the dual constraint relaxation for objective function. The dual constraint relaxation reflects in two parts: on one hand, the objective function based on local region is exploited to replace the point-wise approximation method; on the other hand, considering the variance of local intensity distribution and the reliability of polynomial approximation, we utilize a Gaussian pyramid convolution strategy to devise polynomial fitting. The PPCA method relaxes the constraint condition of objective function so that the piecewise constant image is easily approximated. According to piecewise constant segmentation criterion, we obtain the partial differential equation based on polynomial piecewise constant approximation. Finally, we utilize level set method to construct the energy functional. The visual and quantitative experimental results demonstrate that the proposed PPCA method can yield better results than existing classical local models for segmenting images with serious intensity inhomogeneity.

1. Introduction

In recent years, level set methods [1–5] have been widely and successfully exploited for image segmentation, in which the evolving contour is driven by the partial differential equation until the convergence. Generally, existing level set methods can be classified into two types, i.e. edge-based models [6–9] and region-based models [10–18], respectively. In edge-based models, local gradient information is utilized to drive the active contour toward the object boundaries. However, edge-based models have two limitations: (1) they are sensitive to the position of initial curve; (2) they easily suffer from the serious boundary leakage problem in those images with weak object boundaries. Unlike edge-based models based on image gradient, region-based models utilize the region descriptor to drive evolving curve toward the object boundaries, and usually explore the global region information to stabilize their responses to local variations such as noise and weak object boundaries. As a result, region-based models can obtain better segmentation performance than the edge-based models, especially for those images with noise and weak object boundaries.

Several effective region-based level set models [10–11] have been proposed based on the intensity homogeneity assumption, i.e. image intensities are statistically homogeneous in each region. However, due to various factors such as spatial variations in illumination and imperfections of image devices, the intensity inhomogeneity phenomenon often occurs in real images, which can lead to serious misclassifications for intensity-based segmentation algo-

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rithms [19]. In particular, it is considerably difficult to accurately segment those images with serious intensity inhomogeneity due to the overlaps between the ranges of the intensities in the regions to be segmented. Therefore, it is becoming important to investigate more effective methods for this issue.

Recently, some new local region-based models have been proposed to segment those images with intensity inhomogeneity. A lot of methods were designed based on an assumption that each local region can be described by statistical intensity information of local regions. In this way, local regions can be further divided into object and background regions, respectively. In [20,21], a local binary fitting (LBF) energy with a kernel function was introduced to accurately extract local image information. Lankton et al. [22] proposed a natural framework that allows any region-based segmentation energy to be re-formulated in a local way. In [23], the local image fitting (LIF) energy was proposed and utilized to extract local image information for segmenting images. In [24], the local Chan-Vese (LCV) model was proposed, which combines the global intensity information with local intensity information to segment the images with intensity inhomogeneity. In [25], the local intensity clustering (LIC) model was proposed, which can be considered as a locally weighted K-means clustering method. By introducing local image information, the local region-based Chan-Vese model (LRCV) [26] can effectively segment images with intensity inhomogeneity. Although aforementioned models [20–26] are effective to some extent, they still have some intrinsic drawbacks. For example, the region descriptor in LBF model is only based on the mean intensity information of local region with fixed scale without considering the region variance, which may lead to inaccurate segmentation. This drawback also exists in local region-based (LRB) model [22] and LIF model [23]. Moreover, the Dirac function used in LRB model is restricted in neighborhood of zero level set, which makes the evolving curve act locally. The segmentation results of the LCV and LRCV models rely on the scale of local region descriptor, but the parameter of this scale is difficult to be well defined for the images with serious intensity inhomogeneity. The LIC model [25] does not consider the intensity clustering variance, which may cause inaccurate segmentation similar to the K-means clustering based method [27]. In order to improve the segmentation performance, considering the local intensity variance, some new methods have been proposed [28–33]. Zhang et al. [28] used local information based on the joint density within image patches to perform image partition. The maximum-a-posteriori (MAP) principle with those pixel density functions generates the model. Li et al. [29] proposed a segmentation method based on global and local image statistical information, in which the global energy based on Gaussian model estimates the intensity distributions of the target object and background, and the local energy derived from the mutual influences of neighboring pixels can eliminate the impact of image noise and intensity inhomogeneities. Similarly, the methods of Maximum Likelihood in Transformed Domain Model (MLTDM) [30] and Locally Statistical Active Contour Model (LSACM) [31] use Gaussian distributions with different means and variances to model object with intensity inhomogeneity, and then, the original image intensities are mapped to the other domain so that the intensity distributions can be better separated. In [32], we proposed a novel energy functional by incorporating the local statistical analysis and global similarity measurement, in which the local energy term is based on the intensity statistical analysis of local region and the global energy term is used to minimize the Bhattacharyya coefficients of inside and outside of contour. In [33], the region-based model via local similarity factor (RLSF) was proposed, which relies on local spatial distance within a local window and local intensity difference. For above analysis, it can be seen that these new models [28–33] utilize local statistical information to fit or approximate the intensity distributions of object and background. However, due to the assumption of the piecewise smooth and piecewise constant in local region, these new models [28–33] are not directly suitable for segmenting images with serious shading artifact. Furthermore, it is a challenging task for them to produce accurate segmentation when images are corrupted by noise.

According to above analysis, it can be seen that, on one hand, the variation degrees of intensity inhomogeneity are different in the whole image; on the other hand, existing models cannot design effective approximation condition for image intensity. Therefore, existing models are often unavailable to those images with serious intensity inhomogeneity. In this paper, we propose a novel level set method to effectively segment the images with intensity inhomogeneity. Different from existing models segmenting images directly, the proposed method firstly derives a piecewise constant image by transforming the original image, and then, the piecewise constant segmentation criterion is utilized to construct final energy functional. As a result, in this approximated piecewise constant image, the segmentation can be well performed. Concretely speaking, in order to transform the original image to a piecewise constant image, we firstly define an initial objective function p based on the single pixel approximation, which is called as pointwise approximation. While the objective function satisfies a constraint condition, the approximated piecewise constant image could be obtained. However, the objective function p is unknown and needs to be estimated by optimizing and minimizing final energy functional. In this paper, by introducing the intensity inhomogeneity formulation [34], we reformulate the constraint condition to analyze the feasibility of objective function. In this way, the segmentation problem is changed to the derivation problem of objective function. It should be noticed that the stricter constraint condition shall make the desirable objective function harder to be estimated, vice versa. So, we propose a dual constraint relaxation idea to relax the constraint for objective function. Since the constraint condition of initial objective function is very strict, we utilize each local region to approximate piecewise constant image so as to maintain constant consistency and improve the anti-noise performance of objective function. In this way, the problem of pointwise approximation is transformed to the approximation based on local region, which realizes the first constraint relaxation. Furthermore, considering the variances of local intensity distributions and the reliability of polynomial approximation, we introduce Gaussian pyramid convolution strategy to devise the polynomial fitting based on multi-region. Here, the Gaussian filters, from coarse to fine scales, are utilized to devise polynomial fitting and approximate the piecewise constant image. The polynomial fitting based on multi-region is more robust and effective to images with serious intensity inhomogeneity. And, the polynomial approximation realizes constraint relaxation again by replacing local region-based approximation. That is, the polynomial piecewise constant approximation method is proposed to realize the dual constraint relaxation for initial objective function. Finally, the level set method is applied to construct our image segmentation model. The diagram of the proposed method is depicted in Fig. 1.

Our method has several advantages over existing level set methods for segmenting images with serious intensity inhomogeneity, which are presented as follows.

(1) In our method, by defining an objective function, the original image is transformed to a piecewise constant image approximately so that the piecewise constant segmentation criterion becomes applicable, where constants are utilized to describe image regions. As a result, the piecewise constant energy functional can be derived to segment the images with intensity inhomogeneity. To the best of our knowledge, for the level set models, the proposed method is the first work