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Integrating guided filter into fuzzy clustering for noisy image segmentation

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ABSTRACT

Fuzzy clustering is a classical method to produce soft partitions of data. One of its typical applications is image segmentation. Guided filter, on the other hand, is a powerful edge preserving filter for image smoothing and enhancement. In this work, we design a general framework to improve the fuzzy clustering based noisy image segmentation by integrating the guided filter in a new way. Specifically, the fuzzy clustering is applied on the smoothed image to obtain more homogeneous segments, but the original noisy image is used as the guide of guided filter to post-process the fuzzy memberships in the iteration of clustering. By doing this, the information loss caused by beforehand image smoothing is remedied by the guidance of original noisy image that pulls back subtle details on the boundaries of partitions. In addition, we prove that the memberships post-processed by guided filter still retain the property usually required by fuzzy clustering: for each data point, the sum of its memberships is one. This property and the linear time complexity of guided filter make the proposed information integration framework an efficient way to enhance almost all fuzzy clustering based image segmentation methods. Experiments on synthetic and real images demonstrate that the proposed framework can improve the state-of-the-art fuzzy clustering methods significantly with little run-time overhead.
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1. Introduction

Image segmentation is an essential step in computer vision [1], image analysis [2] and image understanding [3]. Its purpose is to separate the image plane into a certain number of non-overlapping, consistent regions or semantic objects, which share similar characteristics like intensity, tone, color, etc. In the past few decades, many different techniques have been proposed for image segmentation, e.g., variational models [4], edge detection [5], data or graph based clustering methods [6], and recently popularized deep learning approaches [7,8].

Since its inception, fuzzy clustering has attracted great attention from researchers on image segmentation [9]. Fuzzy C-Means (FCM), the most popular fuzzy clustering method, and its enhanced versions have been implemented as powerful tools in image segmentation for their simplicity, fast convergence and performance as an auxiliary procedure in other image segmentation algorithms [10]. In general, fuzzy clustering can achieve good segmentation accuracy in case of handling the image with no or low noise [11,12]. But the segmentation results deteriorate quickly as the image noise level increases.

Unfortunately, the image noise is inevitable in image acquisition and transmission. It usually manifests as random speckles, corrupts true information, and causes the disturbance in images. There are many types of noise like additive noise (e.g. Gaussian noise), impulse noise, mixed noise, and the real-word noise, which can not be modeled by an explicit distribution [13]. For noise suppression in images, many approaches have been proposed. Some algorithms are suggested just for a specified type of noise. For example, Kirti et al. [14] proposed a response median filter for Poisson noise reduction in X-ray images, and Subbuthai et al. [15] presented a filter for restoration of dental images which are corrupted by salt and pepper noise. More algorithms are designed for Gaussian and general noise removal like the non-local means [16], fuzzy image filter [17], BM3D denoising algorithm [18], and so on [19–21].

To reduce the negative effects of noise in fuzzy clustering based image segmentation, the simplest approach is conducting image denoising and applying fuzzy clustering on the smoothed image. In the last few decades, many studies [22,23] have been proposed based on this rationale. For example, Beevi et al. [24] present a segmentation approach by using fuzzy clustering with spatial probability, with the help of image denoise prior to the segmentation.

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Devikar et al. [25] propose the histogram based fuzzy c-means algorithm by using the spatial probability of the neighboring pixel, and the image to be segmented is smoothed by an effective noise reduction algorithm.

For fuzzy clustering algorithms, the memberships of a data point determine its final classification because they indicate how likely or unlikely this data point belongs to each cluster [6]. Therefore, more segmentation methods revise the iteration of fuzzy clustering, especially the calculations of memberships and cluster centers, to suppress the influence of noise and outliers [26]. In most of such studies, the noise type in focus is not specified. For example, Krinidis and Chatzis [27] developed a robust fuzzy local information C-means clustering algorithm (FLICM) to enhance the clustering performance, and in this algorithm, a novel fuzzy local similarity measure was used in the calculation of memberships in this algorithm. But in some studies, the type of image noise is more task related. For example, Gaussian and Rician noises are carefully tackled by [28], in which a modified fuzzy clustering method was proposed by adding a penalty term to the objective function of the standard fuzzy c-means (FCM) for MRI image segmentation. Recently, Sing et al. [29] provided an enhanced version of Pham's algorithm, in which they introduced a probability function that represents the probabilities of neighboring pixels belonging to the class of an appointed pixel to improve MRI image segmentation.

Basically, for better image segmentation in terms of image noise, most of fuzzy clustering based approaches pay close attention on the use of local and non-local spatial information in images. But there are three noticeable problems in these approaches:

- The local spatial information is widely used in fuzzy clustering for the segmentation of images with no or low noise. But the preservation of the gradient information to get more accurate boundaries is still less considered [29].
- For the segmentation of heavy noisy images, some fuzzy clustering methods pretreat the image with denoising techniques to reduce the impact of noise and obtain more homogeneous segmentation results [30]. But such a denoise-then-segment approach is always accompanied by some inevitable boundary information loss compared with applying segmentation over the original noisy image directly.
- Many fuzzy clustering based image segmentation methods use the non-local spatial information [31] to reduce the impact of noise. But the computational cost usually increases sharply because the derivation of non-local information is time consuming and we may need to update and adjust the non-local information in every iteration of clustering [32,33].

To deal with the three problems simultaneously in fuzzy clustering base image segmentation, guided filter [34] is an ideal tool that we can rely on. Guided filter is a local linear transformation that generates the outputs with respect to some guidance information. It is a kind of gradient-preserving image smoothing and enhancement technique with low computational cost. So it has been successfully applied in many image enhancement tasks [35,36]. Indeed, to solve aforementioned problems of previous studies, the image guided fuzzy c-means (IGFCM) [36] has attempted to include the guided filter in the objective function of fuzzy c-means. But this brings a complicate model that is difficult to handle. As a simpler solution, our primitive research [37] suggested the direct application of guided filter on the memberships of fuzzy clustering. But in that research we do not realize that the guided filter has limited capability in suppressing heavy noise. So that work only performs well on the images with low or no noise.

In this study, we will deepen and broaden our research in [37] and overcome its shortcoming in noisy image segmentation. Inspired by [23], which proposes an improved FCM algorithm based on morphological reconstruction and membership filtering, we propose a novel guided filer based information integration framework for fuzzy clustering based noisy image segmentation. More specifically, the noisy image to be segmented is denoised and the fuzzy clustering is applied on the smoothed image to obtain more homogeneous segments. At the same time, the original noisy image is used as the guide of guided filter to post-process the fuzzy memberships in the iteration of clustering. By doing this, the new framework helps the fuzzy clustering to pull back subtle details on the boundaries of regions when partitioning the beforehand smoothed images. In other words, the proposed framework makes better use of the edge-preserving feature of guided filter and remedies its deficiency in suppressing heavy noise.

As the advantages of the proposed framework, the major contributions of this paper are listed as follows:

- We demonstrate that guided filter can be integrated into the state-of-the-art fuzzy clustering methods easily to further improve their performance on noisy image segmentation.
- For heavy noisy image segmentation, with the help of image pre-processing and guided filter, the proposed information integration framework allows fuzzy clustering to obtain both homogeneous segmentation and accurate boundaries of regions.
- Last but not least, we prove that the memberships post-processed by guided filter still keep the property usually required by fuzzy clustering: for each data point, the sum of its memberships is one. This feature and the linear time complexity of guided filter make the proposed framework suitable to enhance almost all fuzzy clustering based image segmentation algorithms without a great revision of their iterations or a large run-time overhead. As a by-product, we mathematically prove the weighting kernel of the guided filter is a normalized one. This fact was only briefly mentioned in previous work [34].

The rest of this paper is structured as follows: some related studies on fuzzy clustering based noisy image segmentation are presented in the next section. The guided filter is also briefed there. In Section 3, we provide the details of the guided filter based information integration framework. The properties of guided filtered memberships are discussed and some illustrative algorithms are provided. In Section 4, we show the testing results on synthetic and real images. The last section includes the conclusion and future work discussions.

2. Related work

In this section, we highlight the standard fuzzy c-means (FCM) and review several variants of FCM that focus on image segmentation. These variants attempt to include additional spatial information in the clustering process by manipulating the calculation of memberships and cluster centers. The guided filter is also briefed at the end of this section.

For consistent notations, throughout the paper we use an uppercase bold letter, such as $\boldsymbol{I}$, to denote an image. The pixels in the image are denoted as I_k, which means the k-th pixel of image $\boldsymbol{I}$. If there are several images or vectors, we use superscripts to distinguish them. For example, the symbol $\boldsymbol{\Phi}^{(i)}$ denotes the membership image corresponding to the i-th cluster.

2.1. Fuzzy c-means

The fuzzy c-means [6] is a soft version of the classical K-means algorithm. Let data X_k ($k = 1, 2, \ldots, N$) denote N pixels in the image $\boldsymbol{X}$, which are to be separated into C clusters or regions. FCM

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