Neurocomputing 106 (2013) 115–125

Contents lists available at SciVerse ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Fuzzy clustering algorithms with self-tuning non-local spatial information for image segmentation

Feng Zhao *,[1]

School of Telecommunication and Information Engineering, Xi'an University of Posts and Telecommunications, Xi'an, PR China

ARTICLE INFO

Article history:
Received 9 May 2012
Received in revised form
27 August 2012
Accepted 30 October 2012
Communicated by X. Gao
Available online 14 November 2012

Keywords:
Image segmentation
Fuzzy clustering
Spatial information
Self-tuning non-local spatial information

ABSTRACT

Due to the limitation of the local spatial information in an image, fuzzy c-means clustering algorithms with the local spatial information cannot obtain the satisfying segmentation performance on the image heavily contaminated by noise. In order to compensate this drawback of the local spatial information, an effective kind of non-local spatial information is extracted from the image in this paper. In the acquisition of non-local spatial information, the filtering degree parameter h is a very crucial parameter and needs to be set appropriately. Instead of using a single h value for all the pixels, the calculation of the adaptive parameter h for each pixel is done by studying the statistical characteristics in its search window. Therefore, the non-local spatial information obtained by using the adaptive h value for each pixel is called self-tuning non-local spatial information. In this paper, two novel fuzzy clustering algorithms using the self-tuning non-local spatial information are proposed. In the first algorithm framework, a spatial constraint term by utilizing the self-tuning non-local spatial information for each pixel is defined and then introduced into the objective function of FCM. This algorithm is called fuzzy c-means clustering algorithm with self-tuning non-local spatial information (FCM_SNLS). In the second algorithm framework, a novel gray level histogram is constructed by using the self-tuning non-local spatial information for each pixel, and then clustering is performed on this gray level histogram. This algorithm is called fast fuzzy c-means clustering algorithm with self-tuning non-local spatial information (FFCM_SNLS). Experimental results show that these two proposed methods are not only more effective than fuzzy clustering algorithms with the local spatial information in noise suppression and edge preservation, but also more robust than fuzzy clustering algorithms with the non-local spatial information.

1. Introduction

Image segmentation [1,2] is one of the most crucial research topics in computer vision and image understanding. In the past few decades, many image segmentation algorithms have been developed [3–9]. Fuzzy clustering algorithms [7,8,10–13] introduce the fuzziness for the belongingness of each image pixel and have been successfully applied to image segmentation. Fuzzy c-means clustering algorithm (FCM) [6] is one of the most widely used fuzzy clustering methods. Due to not considering any spatial information in the image, FCM is very sensitive to image noise and cannot obtain the satisfying segmentation performance on images contaminated by noise.

In order to compensate this drawback of FCM, the spatial information derived from the neighborhood window around each pixel was introduced into FCM. This kind of spatial information derived from the neighbor window around each pixel is called local spatial information. The local spatial information has a lot of expression forms, which bring different types of fuzzy clustering algorithms using the local spatial information. Ahmed et al. [10] proposed FCM_S where the objective function of FCM is incorporated with a spatial neighborhood term and applied the proposed algorithm to the segmentation of MR images. To reduce the computational complexity of FCM_S, Chen and Zhang [14] proposed two variants of FCM_S: FCM_S1 and FCM_S2. These two algorithms adopt the mean and median gray values of the neighborhood window around each pixel respectively, to substitute the neighborhood term of the objective function of FCM_S. As is known, the number of gray levels in the image is generally much smaller than the number of pixels. Based on this, Szilagyi et al. [15] presented an enhanced fuzzy c-means clustering algorithm (EnFCM). In this algorithm, a linearly-weighted sum image is first formed from both the original image and each pixel' neighborhood average gray value, and then clustering is performed on the gray level histogram of the linearly-weighted sum

* Tel.: +86 029 88166140; fax: +86 029 88166379.
E-mail address: fzhao.xupt@gmail.com
[1] Postal address: Mail Box 377, Xi'an University of Posts and Telecommunications, 563 South Chang'an Road, Xi'an 710061, China.

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http://dx.doi.org/10.1016/j.neucom.2012.10.022

image instead of the pixels in the summed image, which results in the acceleration of the image segmentation. Subsequently, Cai et al. [16] proposed a fast generalized fuzzy c-means clustering algorithm (FGFCM). Similar to EnFCM, FGFCM performs clustering on the gray level histogram of a novel non-linearly-weighted sum image. This non-linearly-weighted sum image is constructed from both the original image and the spatial coordinates and the gray values within the neighborhood window around each pixel. Recently, Krinidis and Chatzis [17] presented a fuzzy local information c-means algorithm (FLICM). This algorithm adopts a fuzzy local neighborhood factor to guarantee noise robustness and image detail preservation.

When the image is heavily contaminated by noise, the local spatial information derived from the neighborhood window of pixels may be degraded by the noise. In this case, fuzzy clustering algorithms with the local spatial information cannot obtain satisfactory segmentation results. For every pixel in the image, there are many pixels with a similar neighborhood configuration of it [18]. Compared with using the adjacent pixels, it is more reasonable to use these pixels, which have a similar neighborhood configuration to the given pixel, to obtain its spatial information. This kind of spatial information is called non-local spatial information. In [19], the non-local spatial information was introduced into FCM and a fuzzy clustering algorithm with non-local spatial information for image segmentation (FCM_NLS) was proposed. Experiments on synthetic and real images show that this algorithm is more effective than FCM and fuzzy clustering algorithms with the local spatial information.

It should be pointed out that the fuzzy clustering algorithm with the non-local spatial information in [19] needs to reasonably set a very important parameter, the filtering degree parameter h. The h value is very crucial for the segmentation performance and the selection of h is commonly done manually. In this paper, we propose a strategy to adaptively determine the parameter h. Instead of using a single h value for all the pixels, an adaptive h value for each pixel is calculated. For the given pixel, its h value is obtained by studying the statistical characteristics in its search window. Therefore, the non-local spatial information obtained by using the adaptive h value for each pixel is called self-tuning non-local spatial information. Based on this kind of spatial information, we propose two fuzzy clustering algorithm frameworks. In the first framework, we utilize the self-tuning non-local spatial information for each pixel to define a non-local spatial constraint term, and then introduce this constraint term into the objective function of FCM. This proposed method is called fuzzy c-means clustering algorithm with self-tuning non-local spatial information (FCM_SNLS). In the second framework, we adopt the self-tuning non-local spatial information for each pixel as statistical feature to construct a novel gray level histogram, and then perform clustering on this gray level histogram. This proposed method is called fast fuzzy c-means clustering algorithm with self-tuning non-local spatial information (FFCM_SNLS). Image segmentation experiments show that these two methods outperform FCM, fuzzy clustering algorithms using the local spatial information and fuzzy clustering algorithms using the non-local spatial information.

The rest of this paper is organized as follows. Section 2 reviews some existed local spatial information expression forms. Section 3 introduces the self-tuning non-local spatial information in detail. Then two fuzzy clustering algorithm frameworks with the self-tuning non-local spatial information are presented in Section 4. In Section 5, the proposed methods are verified by segmentation experiments on synthetic and real images. Finally, concluding remarks are given in Section 6.

2. Local spatial information

2.1. Mean and median spatial information

Chen and Zhang [14] utilized the mean and median gray values of the neighborhood window around each pixel to define two kinds of spatial information, which are called mean spatial information and median spatial information, respectively. The mean spatial information of the ith pixel is defined as

$$\delta_i = \frac{1}{S_R}\sum_{p \in S_i} x_p \tag{1}$$

where S_i denotes the set of neighboring pixels falling into a window around the ith pixel and S_R is its cardinality (the number of pixels inside the window). Similarly, the median spatial information for the ith pixel is expressed as

$$\varsigma_i = \mathrm{median}\{x_p, p \in S_i\} \tag{2}$$

2.2. The linearly-weighted local spatial information

To design the more effective spatial information for fuzzy clustering, Szilagyi et al. [15] proposed a kind of spatial information called linearly-weighted local spatial information. For the ith pixel, its spatial information is obtained by using itself and its neighboring pixels in terms of

$$\xi_i = \frac{1}{\beta+1}\left(x_i + \frac{\beta}{S_R}\sum_{p \in S_i} x_p\right) \tag{3}$$

where S_i is a neighbor window around the ith pixel and S_R is the cardinality of S_i. The parameter β controls the effect of the neighborhood term. An image ξ consisting of ξ_i values for all the pixels is called linearly-weighted sum image.

2.3. Non-linearly-weighted local spatial information

Similar to the linearly-weighted local spatial information, Cai et al. [16] proposed another kind of weighted local spatial information called non-linearly-weighted local spatial information. The spatial information of the ith pixel is defined as

$$\zeta_i = \frac{\sum_{p \in S_i} E_{ip} x_p}{\sum_{p \in S_i} E_{ip}} \tag{4}$$

where S_i represents a neighbor window around the ith pixel and E_{ip} denotes a local similarity measure which combines both the spatial coordinates and the gray level values within the neighbor

Table 1
Comparative methods.

Method	Input parameters	Appearance in
FCM_S1 [14]	β, S_R	IEEE SMC Part B (2004)
FCM_S2 [14]	β, S_R	IEEE SMC Part B (2004)
FLICM [17]	S_R	IEEE Image Processing (2010)
FCM_NLS [19]	β, h, r, s	Front. Comput. Sci. China (2011)
FCM_SNLS	β, l, r, s	
EnFCM [15]	β, S_R	25th Annual International Conference of the IEEE EMBS (2003)
FGFCM [16]	λ_s, λ_g, S_R	Pattern Recognition (2007)
FFCM_SNLS	l, r, s	