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Skeleton extraction of boiler flame images based on mathematical morphology

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Abstract: In this paper, a method and algorithm of skeleton extraction based on binary mathematical morphology is presented. Sequential structuring elements (SEs) is also studied, which is the key problem of skeleton extraction. The examples of boiler flame image processing show that the detected skeletons can present the geometric shape of flame images well.

Key words: mathematical morphology; flame image; skeleton extraction

In recent years, the diagnostic systems of boiler combustion based on flame image have been developed rapidly; they are becoming the main method of combustion diagnosis in power stations. In the field of digital flame image processing, the new theory and methods have been performed based on gray value gradient, color, complexity of flame image, etc. These methods have achieved some effect in practice. But these methods have some disadvantages in real time, accuracy and currency[1-5].

Mathematical morphology (MM) is a geometric approach to image processing. It was developed as a powerful tool for shape analysis in binary and gray scale images. The foundations of the MM theory were laid down in 1975 by G. Matheron, in his book *Random Set and Integral Geometry*[6]. MM operations have been applied widely in image filtering, segment, edge detection, and skeleton extraction. As a nonlinear image processing theory, MM has become a cornerstone in image analysis.

In this paper, we introduce an algorithm for extracting the skeleton of flame images based on the MM approach. The skeleton is one of the most important features in flame image processing.

1 Binary Mathematical Morphology (BMM)

The basic concepts and applications of BMM to digital image processing are documented in Refs. [7, 8].The two basic morphology operations used in the shape recognition algorithm are dilation and erosion.

Definition 1 Let $A \subset \mathbf{Z}^2$ be a binary image, and $B \subset \mathbf{Z}^2$ a structuring element (SE). The morphological dilation operation of A by B is defined by

$$A \oplus B = \bigcup_{b_i \in B} Ab_i = \{x \in \mathbf{Z}^2 \mid Ba_i \cap A \neq \varnothing\} \quad (1)$$

where Ab_i indicates the translation of A by b_i:

$$Ab_i = \{x + x_1, y + y_1 \mid (x, y) \in A, (x_1, y_1) \in B\}$$

Similarly Ba_i indicates the translation of B by a_i.

Definition 2 Let $A \subset \mathbf{Z}^2$ be a binary image, and $B \subset \mathbf{Z}^2$ an SE. The morphological erosion operation of A by B is defined by

$$A \Theta B = \bigcap_{b_i \in \check{B}} Ab_i = \{x \in \mathbf{Z}^2 \mid Ba_i \in A\} \quad (2)$$

where $\check{B} = \{-b \mid b \in B\}$ is the reflection of B through the origin of spatial coordinate axes.

2 Hit-or-Miss Transform (HMT)

HMT is a well known morphological template matching technique. In general, the structure of an object can be recognized by the connection of various smaller structures within images. By HMT, we can recognize those structures that are included in the original image, and which are not included.

Definition 3 Let $A \subset \mathbf{Z}^2$ be a binary image, and $B \subset \mathbf{Z}^2$ an SE, which is formed with two structural elements B_1 and B_2, satisfying the conditions:

$$B = B_1 \cup B_2, B_1 \cap B_2 = \varnothing$$

The morphological HMT of A by B is defined by

$$A \otimes B = \{p \mid (B_1)_p \subseteq A \text{ and } (B_2)_p \subseteq A^c\} = (A\Theta B_1) - (\bar{A}\Theta B_2) = (A\Theta B_1) - (A \oplus \check{B}_2) \quad (3)$$

In Fig.1, it's shown how an HMT (A by B) is performed. In this situation, B_1 represents the actual image, and B_2, the background of B, i.e. $B_2 = B - B_1$. $A \otimes B$ not only finds the structure shaped as B_1, but also eliminates the structure shaped as B_2 from the image A.

3 Thinning Transform

According to the above conditions, the thinning

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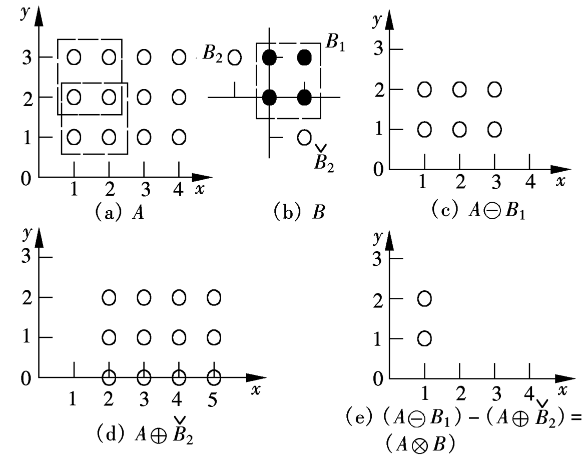

Fig.1 Hit-or-miss transform: $A \otimes B$

transform $A \odot B$ is defined as follows:

Definition 4

$$A \odot B = A - (A \otimes B) \tag{4}$$

According to the definition, the thinning transform $A \odot B$ (image A is thinned by B) means to subtract the result of $A \otimes B$ from the original image A.

4 Skeleton Extraction

In general, the term skeleton has been used to describe a line-thinned structure of an object within a image. The structure summarizes the object's shape information about its size, orientation and connectivity. The representation is detailed by Refs.[9,10]. The skeleton of object A SK(A), viewed as a subset of $\boldsymbol{Z}^2$, is defined as the set of the centers of the maximal disks inscribable inside A. Some objects and their skeletons are shown in Fig.2.

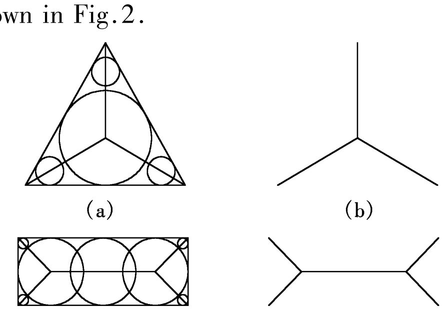

Fig.2 Examples of objects and their skeletons. (a) Example 1; (b) The skeleton of (a); (c) Example 2; (d) The skeleton of (c)

Many algorithms that generate digital skeletons have been proposed, however, most of them produced non-connected skeletons, which are useless for shape-description applications since homotopy is not preserved and characteristic points such as junction points and end-points in the continuous case are lost. In contrast, skeletons generated by a thinning algorithm maintain the conditions for one-pixel thickness and connectivity. The skeleton of an image must satisfy the following conditions: ① In the performance of skeleton extraction, image A must be reduced regularly; ② The homotopy of image A must be preserved; ③ The skeleton obtained must be connective.

The skeleton is defined in Euclidean space according to:

$$A \odot \{T_i\} = (\cdots((A \odot T_1) \odot T_2) \cdots \odot T_i) \tag{5}$$

where $\{T_i\}$ is sequential SEs.

4.1 Thinning structural elements (SEs)

SEs must preserve the homotopy of the image A while the morphological sequential thinning is performed. It was proved by Ref.[11] that the skeleton extracted by the sequential SEs, D_1, E_1 and their three rotations of 90° (see Fig.3), preserve homotopy, one-pixel thickness and eight-connection.

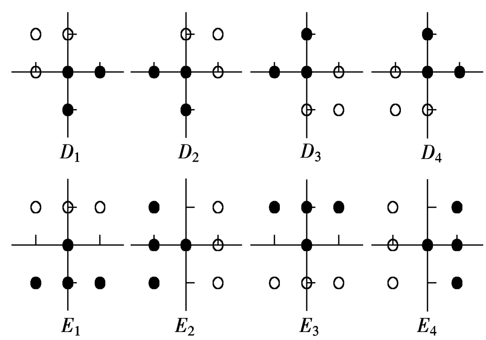

Fig.3 Sequential SEs D_i and E_i

The up-left, up-right, down-right, down-left corner-pixels are eliminated by sequential SEs $D = \{D_1, D_2, D_3, D_4\}$; the up, right, down, left edge-pixels are eliminated by sequential SEs $E = \{E_1, E_2, E_3, E_4\}$.

4.2 Skeleton extraction algorithm

According to the above description, the model of skeleton extraction of image A is established as below:

$$\mathrm{SK}(A) = A \odot \{D_i, E_i\}_m = \{(\cdots((((A \odot D_1) \odot E_1) \odot D_2) \odot E_2) \cdots \odot D_4) \odot E_4\}_m \tag{6}$$

The flow of computational program is

① $m = 1$;

② Image A is sequentially thinned by $D_1, E_1, \cdots, D_4, E_4$, saving the result to A';

③ Comparing A' with A, if $A \neq A'$, let $m = m + 1$, $A = A'$, go to step ②;

④ Ouput A', this is the skeleton of image A.

5 Results and Conclusion

We now present examples of skeleton extraction of boiler flame images. The flame images and their skeletons are shown in Fig.4 and Fig.5. Compared the original flame images with their skeletons, we find that the connected skeletons can represent the flame images' geometric shape, and they can also preserve the homotopy of the original flame images.

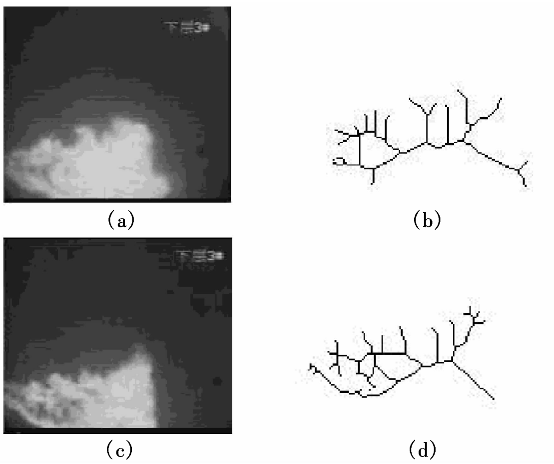

Fig.4 Down-layer 3# flame images and their skeletons. (a) Original flame image 1; (b) Skeleton of (a); (c) Original flame image 2; (d) Skeleton of (c)

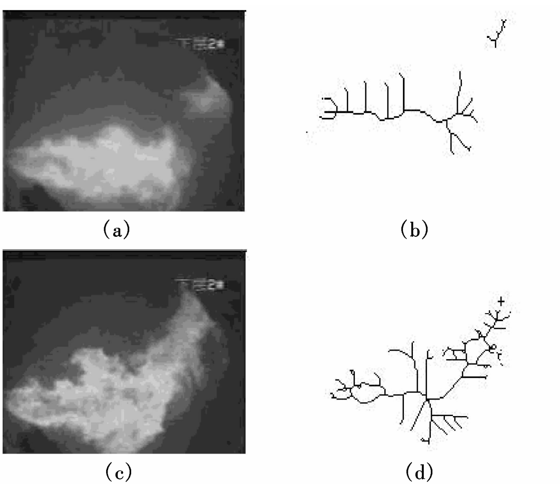

Fig.5 Down-layer 2# flame images and their skeletons. (a) Original flame image 3; (b) Skeleton of (a); (c) Original flame image 4; (d) Skeleton of (c)

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基于数学形态学的锅炉火焰图像骨架提取

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摘　要　本文基于二值数学形态学,建立了数字图像骨架提取方法,并给出了相应的算法.同时,对结构元素序列进行了研究,结构元素序列的选取是骨架提取的关键.最后,应用数字图像骨架提取算法,对锅炉火焰图像进行了处理.处理结果表明,所提取的骨架能够准确地描述火焰图像的几何形状.

关键词　数学形态学；火焰图像；骨架提取

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