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RESEARCH ARTICLE

YUAN Wei-qi, LI De-sheng

Edge detection based on directional space

Abstract A new method for edge detection based on directional space is proposed. The principle is that: firstly, the directional differential space is set up in which the ridge edge pixels and valley edge pixels are abstracted with the help of the method of logical judgments along the direction of differential function, forming a directional roof edge map; secondly, step edge pixels are abstracted between the neighboring directional ridge edge and directional valley edge along the direction of differential function; finally, the ridge edge map, valley edge map and step edge map gained along different directions are combined into corresponding ridge edge map, valley edge map and step edge map. This method is different from classical algorithms in which the gray differential values of the mutual vertical direction are combined into one gradient value. The experiment of edge detection is made for the images of nature scenery, human body and accumulative raw material, whose result is compared with the one of classical algorithms and showing the robustness of the proposed method.

Keywords Edge detection, Directional space, Roof edge, Step edge

1 Introduction

In computer vision, edge detection is a process which attempts to capture the significant properties of objects in the image. These properties include discontinuities in the photometrical and geometrical and physical characteristics of objects. Such information gives rise to variations in the grey level image. The most commonly used variations are discontinuities (step edges), local extremes (line edges) and 2-D features formed where at least two edges meet (junctions).

The purpose of edge detection is to localize these variations and to identify the physical phenomena which have produced them. Edge detection must be efficient and reliable for the validity, efficiency and possibility of the completion of subsequent processing stages to rely on it. To fulfill this requirement, edge detection should provide all significant information about the image. For this purpose, image derivatives are computed. However, differentiation of an image is an ill-posed problem that image derivatives are sensitive to various sources of noise, i.e., electronic, semantic, and discrimination/quantification effects. To regularize the differentiation, the image must be smoothed. However, there are undesirable effects associated with smoothing, i.e., loss of information and displacement of prominent structures in the image plane. Furthermore, the properties of commonly-used differentiation operators are different and therefore they generate different edges. It is difficult to design a general edge detection algorithm that performs well in many contexts and captures the requirements of subsequent processing stages. Consequently, over the history of digital image processing, a variety of edge detectors have been devised, which differ in their purpose (i.e., the photometrical and geometrical properties of edges which they are able to extract) and their mathematical and algorithmic properties.

The general method of the edge detection is that the edge intensity is calculated in a window, and then the thresholding of the edge intensity is decided in the whole intensity space, and the image is classed as the edge pixel and non-edge pixel by the edge intensity of every pixel point. Because the edge intensity is different in different regions, some edge pixels are lost, and some non-edge pixels are marked as the edge pixel after thresholding, and the continuity and reality of the result of the edge detection is not insured. On the other hand, the detected edge commonly has over-one-pixel width, and the detected edge width depends on the thresholding.

The early calculation for the edge intensity mainly

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YUAN Wei-qi (✉)
School of Information Science and Engineering, Shenyang University of Technology, Shenyang 110023, China
E-mail: yuanwq@sut.edu.cn
LI De-sheng
College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100022, China

depends on differential calculation, which includes all kinds of gradient operators, e.g., Roberts, Sobel, Prewitt, Kirsch, Laplace operator, etc.. All of these operators have higher sensitivity to the edge and the noise. Because they cannot strictly distinguish between the edge and the noise, their applications are limited. To restrain noise, in recent years, some mathematical methods, e.g., neural network, wavelet analysis, fuzzy set theory, surface-fitting, statistical classifier, co-occurrence matrix, etc., have been used to calculate edge intensity. However, they do not get rid of the restriction of the calculation of edge intensity in the window and the setting of thresholding, showing no outstanding improvement in the results of edge detection. Moreover, the calculation of edge intensity is becoming increasingly complicated.

This paper presents a new method of edge detection. It turns the three-dimensional gray image space into a combination of several two-dimensional directional gray image spaces, where the edge pixels are extracted and combined in the directional space to form the edge map. This method gets rid of the restriction of calculation of edge intensity and thresholding. In this way, the edge can be directly extracted by logic judgments. At the same time, roof edge and step edge can be obtained as well.

2 Basic concept of directional space

Suppose that the digital image is composed of $M \times M$ pixel matrix, the direction of the row and column pixels are indicated by X and Y respectively in Descartes coordinate system, the direction of each pixel's gray level is indicated by Z, and the gray level of the pixel (i, j) is indicated by $f(i, j)$. The set of gray level of all of the pixels in an image makes up the gray level curved surface called the gray level space. The distribution of gray level along the section of any direction of gray level space is a waved curve. The peak of the curve corresponds to the image's ridge edge, and the valley to the valley edge.

Definition: The distribution of gray level along the section of any direction of gray level space is defined as directional gray level function $f_{dnm}(i, j)$, where the subscript d indicates the direction of the directional gray level function, i.e., the included angle of the projection of the function to the axis X in the Descartes coordinate. The subscript n indicates the nth directional gray level function along d direction in the gray level space. The subscript m indicates the mth pixel of the nth directional gray level function along d direction in the gray level space. The set of directional gray level function along d direction makes up of the d directional gray level space.

Hypothesis 1 The gray level space of the digital image can be denoted by the gray level space of any one (and only one) direction. When considering the position relation between pixels in gray level space, the direction of the directional gray level function can be realized more easily if they are taken as 0°, 45°, 90°, and 135°.

Therefore, the gray level space of the digital image can be expressed by the directional gray level function as follows:

$$F_d = \sum_{n=0}^{M-1} \sum_{m=0}^{M-1} f_{dnm}(i, j) \tag{1}$$

where, $m = 0, 1, \cdots, M-1$, $n = 0, 1, \cdots, M-1$, $d = 0°, 45°, 90°, 135°$.

It is worth noticing that, there is a one-one corresponding relation between the above sequential number m and pixel position (i, j) in the gray level space only at the two directional gray level function along direction 0° and 90°. For example, for the directional gray level function along direction 0°, the sequential number m is equal to the pixel space position j. But for the directional gray level functions along direction 45° and 135°, there is no one-one corresponding relation between sequential number and pixel space position. Therefore, in this paper, subscript m is used to express the sequential number, and point (i, j) is only used to indicate corresponding pixel.

Hypothesis 2 A differential level space of the digital image is formed by adding several directional differential level spaces.

Suppose $f'_{dnm}(i, j)$ expresses difference extreme value of the mth pixel in nth directional difference function along direction d, and the difference extreme of the pixel (i, j) along direction d is given by:

$$f'_{dnm}(i, j) = f_{dnm}(i, j) - f_{dn(m-1)}(i, j) \tag{2}$$

The directional difference level space of direction d is expressed as:

$$F'_d = \sum_{n=0}^{M-1} \sum_{m=0}^{M-1} f'_{dnm}(i, j) \tag{3}$$

Then the differential level space of the digital image can be expressed as:

$$F' = \sum_d F'_d, \quad d = 0°, 45°, 90°, 135° \tag{4}$$

Equation (4) only describes that the differential level space consists of four directional difference level spaces, giving no information about the relationship among difference extreme value of each point, which should be mentioned.

Hypothesis 3 At some point between the arbitrary adjacent directional valley edge point and directional ridge edge point of the directional gray level function, there is one and only one directional step edge point, which is supposed to be located at the point corresponding to direction difference extreme value between above two edges.

Hypothesis 4 The directional edges detected in directional space (including roof edge and step edge) may be added up to form a real edge corresponding to the original image.

3 Edge detection of directional space

In the difference level space along direction d, the following hypothesis is proposed:

If $f'_{dnm}(i,j) > 0$, it indicates the increase of the gray level, if $f'_{dnm}(i,j) < 0$, it indicates the decrease of the gray level.

Therefore, there exists one fact in the following at the mth pixel point of the nth gray level function:

If the following inequality is satisfied,

$$f'_{dnm}(i,j) > 0 \text{ and } f'_{dnm(m+1)}(i,j) < 0 \tag{5}$$

it indicates that there is a direction ridge edge at this point, which is represented by logic 1, namely, $R_{dnm}(i,j) = 1$.

If the following inequality is satisfied,

$$f'_{dn(m+1)}(i,j) < 0 \text{ and } f'_{dnm}(i,j) > 0 \tag{6}$$

it indicates that there is a direction valley edge at this point, which is represented by logic 2, namely, $R_{dnm}(i,j) = 2$.

If at the mth pixel point along the direction d, the following relations are satisfied,

$f'_{dnm}(i,j) < 0$ or $f'_{dnm}(i,j) > 0$, and

$$f'_{dn(m+1)}(i,j) = 0 \tag{7}$$

direction difference value at the point of (m+2), (m+3), ⋯, (m+p), ⋯, M is judged respectively (where: $(m+p) < M$), till $f'_{dn(m+p)}(i,j) \neq 0$.

If the signs of $f'_{dn(m+p)}(i,j)$ and $f'_{dnm}(i,j)$ are opposite to each other, it indicates that valley edge or ridge edge exists between m and $(m+p)$. The edge point is set at $(m+p/2)$ if p is even, or at $(m+(p+1)/2)$ if p is odd.

If the signs $f'_{dn(m+p)}(i,j)$ and $f'_{dnm}(i,j)$ are the same, it indicates that neither valley edge nor ridge edge exists. Therefore, above pixel is dealt with as non-edge pixels and is labeled as logic "0", namely, set $R_{dnm}(i,j) = R_{dn(m+1)}(i,j) = \cdots = R_{dn(m+p)}(i,j) = 0$.

All of the pixels in the directional difference space are scanned and marked as logic 0, 1, and 2 respectively, which forms forming a directional roof edge mapping space R_d. The d directional roof edge mapping space is given by:

$$R_d = \sum_{n=0}^{M-1}\sum_{m=0}^{M-1} R_{dnm}(i,j) \tag{8}$$

Between arbitrary neighboring valley edge and ridge edge at the d directional roof edge mapping space, there is a gray difference maximum point $f'_{dm}(i,j) = \max f'_{dm}(i,j)$, which is then defined as step edge.

Scan all of the pixels in the directional roof edge mapping space. If the condition of the step edge is satisfied, this pixel point is marked as $S_{dnm}(i,j) = 3$, otherwise, $S_{dnm}(i,j) = 0$. Therefore, a step edge directional mapping space is formed. The d directional step edge mapping space is expressed as follows:

$$S_d = \sum_{n=0}^{M-1}\sum_{m=0}^{M-1} S_{dnm}(i,j), \quad S_{dnm}(i,j) = 0, 3 \tag{9}$$

Several directional edge mapping spaces are applied with 'or' operation, which forms edge mapping spaces finally, namely, roof edge mapping space which is expressed as follows:

$$R = \sum_d R_d, \qquad d = 0°, 45°, 90°, 135° \tag{10}$$

The step edge mapping space is expressed as follows:

$$S = \sum_d S_d \tag{11}$$

The valley edge appears at the point where the difference value alternates from negative value to positive one. The ridge edge appears at the point where the difference value alternates from positive value to negative one. While the step edge appears at the point where there is a maximum difference value between adjacent valley edge and ridge edge.

The step edge detection must be based on the roof edge mapping space and directional difference level space. The functional value of the roof edge mapping space consists of 0, 1, and 2, where '0' stands for non-edge pixel, '1' for valley edge pixel, and '2' for ridge edge pixel.

For each scanning row, the position of searching ending point is decided first. To do this, valley edge or ridge edge is searched from right side to left side. As long as any of the above condition is satisfied, the corresponding pixel is regarded as a searching ending point. Because the roof edge mapping space consists of 0, 1, and 2, as long as $R_{dnm}(i, j) > 0$ is satisfied, this pixel is regarded as the position of searching final point and labeled as T_3.

Thereafter, all of the pixels of scanning row are searched again from left side to right side. If $R_{dnm}(i, j) > 0$, the corresponding pixel is regarded as a searching beginning point in the distance of a waved function and labeled as T_1, where T_1 is the beginning point of either up or down slope. Search to the right from T_1, if the following formula is satisfied:

$$R_{dnm}(i,j) + R_{dn(m+T_1)}(i,j) = 3 \tag{12}$$

set $T_2 = m$, i.e., T_2 is regarded as the ending point of the searching distance.

In the interval (T_1, T_2), the difference maximum is searched. If it satisfies:

$$f'_{dnT}(i,j) = \left|\max\{f'_{dnm}(i,j)\right| \; m = T_1, T_2+1, \cdots, T_2\}\right| \tag{13}$$

then set $S_{SdnT}(i,j) = 1$, i.e., this pixel is marked as contour edge pixel.

If Eq. (13) and $f'_{dnm}(i,j) < 0$ are satisfied at the same time, it means that this point lies at the falling side of the waved function, with both $f_{dn(m-1)}(i, j)$ and $f_{dnm}(i, j)$ being regarded as step edge. Thus, the pixel near the valley edge is defined as step edge, where $f_{dnm}(i, j)$ should be marked as step edge. On the other hand, if both Eq. (13) and $f'_{dn(m-1)}(i,j) > 0$ are satisfied at the same time, it expresses that this point lies at the ascending side of waved function.

Therefore $f'_{dn(m-1)}(i, j)$ should be marked as step edge.

Because of the existence of the grey level resolution of the digital image, there appears differences in the grey level of each pixel, which are much smaller than that of the edge point. Accordingly, the grey level threshold should be made quite suitable. The experimental results show that, if there are only one or two grey levels, it can fit the requirements. If the grey level of one point is bigger than the threshold, it is said to be the edge point, not effecting the extraction of the edge pixel.

The edge detection method of directional space is summarized in the following:

1) Gray level space is decomposed into directional gray level space, with directional gray level function gained.

2) Directional gray level space is mapped to the directional difference level space, with directional difference level function gained.

3) Ridge and valley edge pixels are given on the basis of the directional difference level function, with directional roof edge mapping space formed.

4) Step edge pixel is decided according to directional roof edge function and directional difference level function, forming the directional step edge mapping space.

5) Directional roof edge mapping spaces are merged to form the roof edge mapping space while directional step edge mapping spaces are merged to the step edge mapping space.

4 Experiments and result analysis

Figure 1(a) presents the original image from the piled cement pellet. In this paper, the experiments of the edge detection are carried out respectively in the direction of 0° and 90° in difference spaces. Fig. 1(d) shows the detection result of the valley edge. As shown in Fig. 1, a whole valley edge map can be acquired by a simple adding operation to the results extracted in the 0° and 90° directions. The location of the extracted skeleton edge is accurate compared with the original image. It can also be seen that there are some broken points in the edge map by further observation. Analysis shows that there are two cases for it: one is that valley doesn't appear on the position of broken points, the other is that valley doesn't appear in the 0° and 90° directions but on other directions.

For the former, it can be seen that the broken points lie in some points between two pellets when comparing with the original figure. As shown in Fig. 2, the edge is located on two sides of the pellets, the valley is an inclined plane, which may be the surface of the under layer pellet or the shadow. According to the difference edge detection method, the point dividing the left edge from valley inclined plane is the border at which the sign of difference value changes and is marked as the skeleton edge. However, the sign of difference value doesn't change at the point dividing the right edge from the valley inclined plane, for which reason, this point is not marked. As a result, there is a losing of edge. Actually, in Fig. 2, the contour marked on the left is not only skeleton edge but also contour edge, while the contour marked on the right is merely the contour edge. If starting from the skeleton edge to look for the contour edge, both the two contour edges above should be determined. For the latter, the only resolution is that the edge-searching steps are added respectively in the 45° and 135° directions.

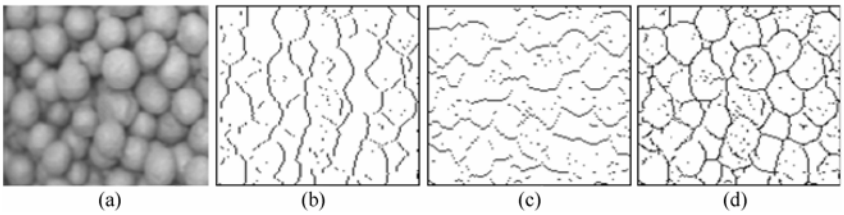

Fig. 1 Detection result of valley edge. (a) Original figure; (b) Detection results along 0° directions; (c) Detection results along 90° directions; (d) Result by merging two directions

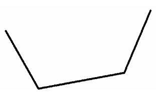

Fig. 2 The edge between two pellets.

Figure 3 shows the result of the ridge edge detection. Fig. 3(b) shows the edge mapping at the 0° direction, Fig. 3(c) at the 90° direction, Fig. 3(d) shows edge mapping, where real line denotes valley edge and dashed line denotes ridge edge.

As shown in Fig. 3, the ridge edge lies between two adjacent valley edges. On the other hand, the valley edge lies between two adjacent ridges, which are in correspondence with the actual cases. By further observation, it can be seen that the extracted valley edge along the 0° direction has good continuity, while the one along the 90° direction has bad continuity. This phenomenon is possibly caused by the fact that the light is at an angle to 0° axes.

Figure 4 shows the result of the step edge detection, in which (b) shows the directional step edge map at the 0° direction, (c) shows the one at the 90° direction, and (d) shows the merging results of the two above.

Figure 5 shows the results extracted by several classical edge detection operators.

Figure 6 to Fig. 8 give the experimental results of the proposed method and other two methods which are considered at present as the better ones, namely Marr-Hildreth method [6] and Canny method [7]. The results

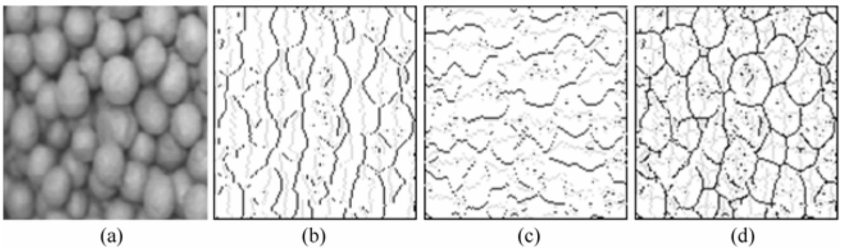

Fig. 3 Detection result of ridge edge. (a) Original figure; (b) Extracted results along 0° directions; (c) Extracted results along 90° directions

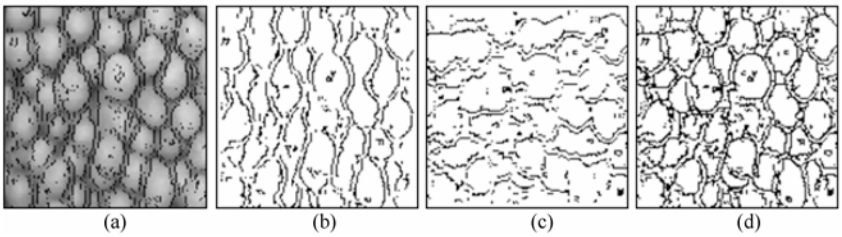

Fig. 4 Result of the step edge detection. (a) Original image and marked result; (b) Result of step edge detection along 0° directions; (c) Result of the step edge detection along 90° directions

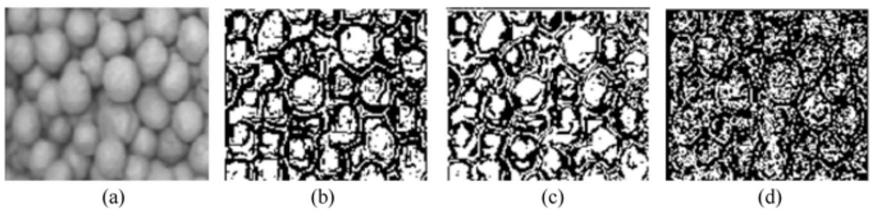

Fig. 5 Results given by sever of classical edge detection. (a) Original image; (b) Result abstracted by Sobel operator; (c) Result extracted by Roberts's operator; (d) result extracted by Laplacian operator

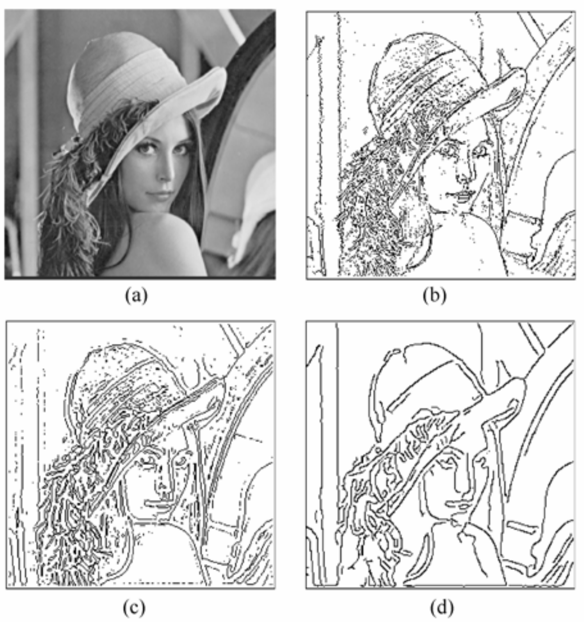

Fig. 6 Experiments results on original image 1. (a) Original image 1; (b) Result of proposed method; (c) Result extracted by Marr-Hildreth operator; (d) Result extracted by Canny operator

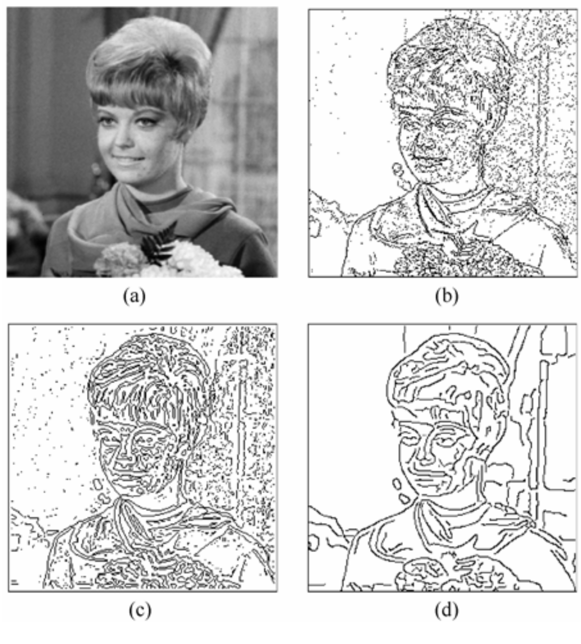

Fig. 7 Experiments results on original image 2. (a) Original image 2; (b) Result of proposed method; (c) Result extracted by Marr-Hildreth operator; (d) Result extracted by Canny operator

show that, the location precision of the proposed method is much better than the other methods, with very clear details. While Marr-Hildreth method produces many redundant lines, and Canny method loses many parts of image details.

5 Conclusions

An edge detection method based on direction space is presented in this paper. The direction edge map spaces are formed by the detection of different directional edges, which are then merged to form the edge map of the whole image. The direction space based edge detection algorithm has the following characteristics:

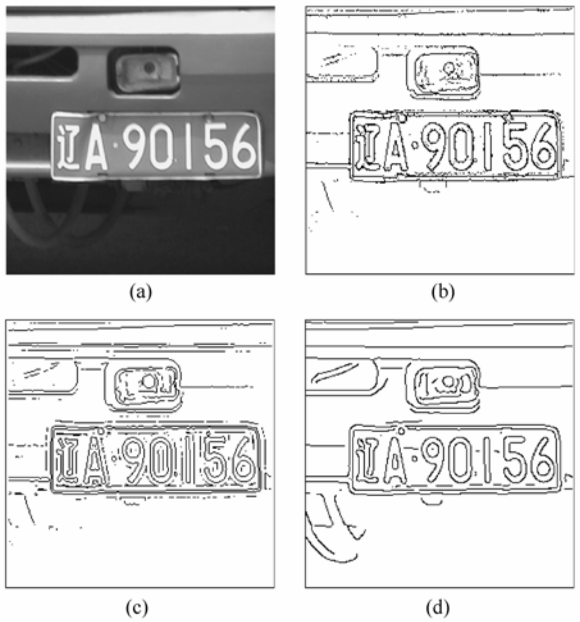

Fig. 8 Experiments results on original image 3. (a) Original image 3; (b) Result of proposed method; (c) Result extracted by Marr-Hildreth operator; (d) Result extracted by Canny operator

1) The detection algorithm depends on logic judgment, without computation of edge intensity thresholding.

2) Detected edge width is made up of only one pixel. The edge location is accurate.

3) Valley edge, ridge edge and step edge are given in the final results at the same time.

The experimental result shows that this method is effective. Further work is to carry out edge detection at the direction of 45° and 135°. Influence of the fine changes of image gray level on the result also needs to be solved.

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