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An Improved Algorithm of Image Edge Detection Based on the Degree Connection Situation

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Abstract: Aiming at the defect of the poor ability to suppress the noise of the algorithm of image edge detection, as well as too much sensitive to the noise, an improved algorithm of image edge detection based on set pair analysis by combining trend relationship of the degree connection situation with the algorithm of half-neighborhood adaptive image edge pick-up is presented in this paper. The core of the algorithm is first to detect the most possible direction of the edge by using the biggest value of Degree Connection Situation–c/a, then calculate absolute value of the D-value between the average value of three points and the average value of five points and the standard deviation value of all the points value in the 8-neighborhood, and, at last, decide whether the center point is on the edge according to the threshold value of the standard deviation value. The result of the simulation indicates that, without any processing to the image, the improved algorithm is not only accurate but also legible in object brim pick-up, compared with the algorithm in literature; furthermore, the noise is greatly suppressed by using it.

Keywords: half-neighborhood, set pair analysis, image edge detection, the situation of degree connection

1. Introduction

Edge is the most important feature of image for vision. Because edge can not only outline the shape of the region, defined locally, but also can convey most of the image information, so edge detection can be seen as a key technology for dealing with many problems, such as handwriting identification, face recognition, image coding, compression, texture analysis, etc. Traditional edge detection algorithms, such as Sobel operator [1], Canny operator [2], and Laplacian operator, etc., all use the first and second derivatives or gradients of the image to detect edges. Generally, the horizontal and vertical gradient images of the original image are first calculated, and then, the modulus and argument values of the gradients are obtained based on these two gradient images. Finally, the modulus maximum is calculated along the argument direction, which allows the detection of image edges. However, these algorithms are very sensitive to noise, have poor denoising capabilities, and introduce noise while extracting edges. Based on the Sobel operator, Li and Qu [3] improved it by considering four sets of point pairs formed by the differences between the gray values of eight natural adjacent points in the horizontal, vertical, and diagonal directions and the average gray value of the entire image as set pairs, and evaluating them using the situation method of connection degree. This method has strong noise immunity, but the algorithm that uses the mean value of the same degree to determine whether it is a boundary point cannot handle situations where the boundary pixels are close to each other. For example, suppose the pixel $f(i, j)8$ has the following 8 neighboring pixel values shown in Table 1.

The mean value of the same degree of 0.8909 is much larger than the mean value of the opposite degree of 0.1091, which indicates that the method in Li and Qu [3] is only suitable for image edge detection with large pixel differences and particularly clear boundaries. This article proposes a new image edge extraction method based on the half-neighborhood and set pair analysis method. The method first detects the most likely image edge direction using the connection degree trend and then calculates the absolute value of the difference between the three-point mean and the five-point mean of the image edge, and the standard deviation of all points in the 8-neighborhood. Finally, it determines whether the center point is an edge based on the threshold value of the standard deviation. Experiments have shown that the method proposed in this paper can effectively detect image edges with similar pixels and is more effective than the half-neighborhood and the method proposed in Li and Qu [3].

In recent years, with the development of deep learning technology, edge detection operators have produced some advanced techniques such as U-Net, holistically-nested edge detection (HED), and Richer Convolutional Features for Edge Detection (RCF).

U-Net is a classic deep learning model commonly used for medical image segmentation [4]. It employs an encoder-decoder structure that can learn multi-level features of images, enabling

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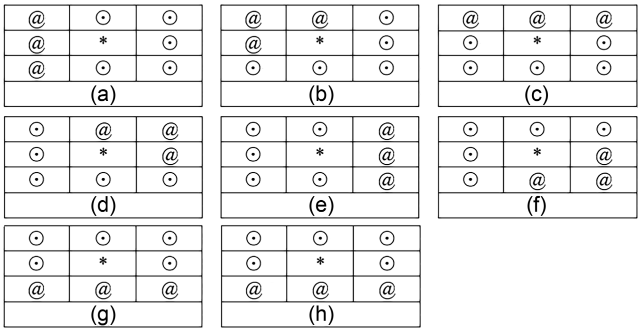
Table 1
8-neighborhood

188	185	186
177	$f(i, j)$	176
164	165	169

Figure 1
Half-neighborhood detection



accurate edge detection; HED is a fully convolutional network for end-to-end learning from training images to edge maps. It uses multi-scale and multi-level feature fusion to capture edge information at different scales; RCF proposes a richer feature fusion strategy that enhances the accuracy of edge detection by combining features from different layers [5].

2. Literature Review

2.1. Half-neighborhood

Using the half-neighborhood to detect whether a pixel point is on the edge involves analyzing the eight neighboring pixel points around it, dividing them into two groups, and grouping the three consecutive pixel points in a clockwise direction into one group, with the remaining five pixel points forming the second group [6]. There are 8 cases, as shown in Figure 1 (* represents the detected pixel point, ⊙ represents the first set of pixel points, and @ represents the second set of pixel points).

Let N represent the set of 8 neighboring points of the center point *, the set N as the average gray value of set N, M_3 is the set of 3 consecutive adjacent points in N, $\overline{M}_3$ is the gray level mean value of the M_3 set. M_5 is a set of 5 consecutive neighbors in N, and $\overline{M}_5$ is the gray level mean value of the M_5 set. The $f(i, j)$ represents the gray value of the (i, j) pixel, and T represents the given threshold. The specific implementation steps are as follows:

First, select a group of these 8 situations to maximize the value of $|\overline{M}_5 - \overline{M}_3|$. This is the most likely combination of boundaries. It can be determined according to the following formula:

$$f(i, j) = \begin{cases} \overline{N}, |\overline{M}_5 - \overline{M}_3|_{\max < T,\ \text{The boundary is not obvious}} \ (1) \\ \overline{M}_5, |\overline{M}_5 - \overline{M}_3|_{\max < T,\ \text{The boundary is obvious}} \ (2) \end{cases}$$

Due to the use of multi-pixel mean value judgment in the half-neighborhood algorithm, it is more capable of protecting the boundary and overcoming noise interference than the single-pixel point judgment method [7]. However, the actual extraction effect is highly dependent on the given threshold value T. In practical applications, it is difficult to ensure that the pixel of the center point is exactly equal to the average value of 8 pixels or the average value of 5 pixels, which is subject to certain limitations. In addition, if this algorithm is used to handle situations such as the presence of multiple parallel $|\overline{M}_5 - \overline{M}_3|$ maxima, it will increase the false positive rate.

2.2. Degree of connection

Set theory, as the foundation of mathematics, was proposed by Georg Cantor more than 100 years ago, and paradoxes in set theory have always been a focus of controversy among mathematicians [8]. Set pair analysis theory believes that there is no purely single set conceptually. For example, given a positive set, it actually gives a negative set at the same time; given a set of people who support a certain plan, it actually gives a set of people who oppose the plan at the same time; because whether it is positive or negative, whether it is support or opposition, whether it is attack or defense, whether it is buyer or seller, etc., they all exist relative to each other. Without one side, the other side will no longer exist. From this perspective, understanding the paradox of sets will reveal that the research base point is no longer “sets” but “set pairs.”

Analyzing the characteristics of a set pair under a certain problem, we obtain a total of N characteristics, where S characteristics are common to both sets, P characteristics are opposite, and the remaining $F = N\text{-}S\text{-}P$ characteristics are different and not opposite [9]. The ratio $a = S/N$ is the degree of identity of the set pair, $b = F/N$ is the degree of difference, and $c = P/N$ is the degree of opposition. The degree of connection u of the set pair is expressed as:

$$\mu = \mathrm{a} + \mathrm{bi} + \mathrm{cj} \tag{1}$$

where i is the mark of difference degree, and j is the mark of opposite degree. With the concept of connection degree, we can describe problems that were inaccurately described or could not be described in the past.

For example:

1) If there is a rule “If the starter makes a harsh noise, it indicates that the probability of the starter being bad is 0.75,” according to probability theory, the above rule implies that there is another rule “If the starter does not make a harsh noise, it indicates that the probability of the starter being good is 0.25.” But in many cases, people do not accept such rules. But using the degree of connection can be clearly expressed as $\mu = 0.75 + 0.25i$.
2) Traditional methods cannot distinguish between the following two problems with a 0.7 probability: “There are n apples on the table, and 7/10 of them are taken away,” and “The probability of rain in this season is 0.7, and the probability of rain tomorrow is predicted to be 0.7.” These two problems are represented by the degree of connection as follows: $\mu_1 = 0.7 + 0.3i$ and $\mu_2 = 0.7 + 0.3j$. From the formal formula, linking mathematics can distinguish these two different 0.7 values.
3) There is an idiom in our country: “Three smelly cobblers can make a Zhu Ge Liang,” some people use $1 + 1 + 1 > 3$ to express it, but from a mathematical point of view, this expression is wrong. The actual problem shows that “$1 + 1 + 1 > 3$” is correct. Because, with

the same three people, good cooperation can have the effect of "1 + 1 + 1 > 3," while poor cooperation can lead to "1 + 1 + 1 < 3." Since it is a fact, there will be a theory of uncertainty to explain it. In connection with mathematics, the concept of connection number is introduced to answer this question: $\mu = 1 + 2i$.

4) Compare the closeness of the pair of positive integers 3 and 2 with the pair of positive integers 6 and 4. Generally, people know that the relationship between 1000 and 999 is closer and more intimate than that between 3 and 2. It is determined by the ratio method, because 999/1000>2/3, but the ratios of 3 and 2 and 6 and 4 are the same. Using traditional mathematics cannot accurately describe which one is closer to the other. Introduce the opposite interval into the connection mathematics to obtain the corresponding connection degree:

$$\mu(2,3) = 2/3 + (1/12)i + (1/4)j,$$

$$\mu(4,6) = 4/6 + (2/105)i + (11/35)j$$

Because $1/4 < 11/35$, so 3 and 2 are closer than 6 and 4.

In short, the concept of connection degree implies a theory of uncertainty that is different from traditional probability theory and fuzzy set theory, but it also includes both under certain conditions. There is a relationship between the degree of sameness a, the degree of difference b, and the degree of opposition c. If they are ranked, the concept of the same, different, and opposite situations can be obtained, which can depict various situations of uncertainty [10]. The degree of connection also contains rich geometric information, which can be converted into connection angles and connection vectors.

2.3. Contact degree and situation

In the definition of the degree of connection, the magnitude relationship between the coefficients a, b, and c determines the trend of change in the set pair consisting of the input pattern feature set and the reference pattern feature set, known as the degree of connection potential (set pair potential).

Definition 1: Let A and B be set pairs, with B as the base point. The degree of connection between set pairs A and B is given by $\mu = a + bi + cj$. When $c \neq 0$, the ratio a/c is called the relative certainty set pair potential, and is denoted as SHI1(A, B) = a/c, or simply SHI1 = a/c. When $c = 0$, the ratio a/b is called the relative uncertainty set pair potential, denoted as SHI2(A, B) = a/b, or simply SHI2 = a/b.

SHI1 and SHI2 cannot exist simultaneously, and the set pair potential reflects the tendency for A to tend towards B.

For example, if an input pattern A has 6 features, 3 of which match the reference pattern, 2 of which do not match, and 1 of which is uncertain, then using reference pattern B as the base point, the connection degree of the input pattern can be obtained as follows: $\mu = 3/6 + (1/6)\ i + (2\ /\ 6)\ j$, where SHI1 = 1.5.

Definition 2: Let the relative certainty potential of set pair A, B be SHI1. If SHI1>1, A and B are said to have the same potential. If SHI1<1, A and B are said to have the opposite potential. If SHI1 = 1, A and B are said to have the equal potential.

For example, in the above example, SHI1=1.5 means that the trend of the input pattern matching the reference pattern is 1.5.

Definition 3: Under the premise of set pair synergy, if $b < c$ is satisfied, then A and B are said to have strong synergy. If $a > b >$ c is satisfied, then A and B are said to have weak synergy. If $b > a$ is satisfied, then A and B are said to have slight synergy. If $b = 0$ is satisfied, then A and B are said to have quasi-synergy.

When there is a strong homogeneity between sets, it indicates that the similarities, differences, and opposites between the two sets are dominated by the "same trend." In the above example, pattern A can be identified as the dominant one [11]. The quasi-homogeneity indicates that pattern A can be identified as clearly determined.

Definition 4: Under the premise of set pair anti-potential, if $b < a$ is satisfied, then A and B are said to have strong anti-potential. If $b > a$ && $b < c$ is satisfied, then A and B are said to have weak anti-potential. If $b > c$ is satisfied, then A and B are said to have weak anti-potential. If $b = 0$ is satisfied, then A and B are said to have quasi-anti-potential.

Definition 5: Under the premise of set pair balance, if $a > b > 0$ is satisfied, then A and B are said to have strong balance. If $b = a$ is satisfied, then A and B are said to have a weak balance. If $b > a$ is satisfied, then A and B are said to have a slight balance. If $b = 0$ is satisfied, then A and B are said to have quasi-balance.

Definition 6: Given a pair of relatively uncertain sets, if $a < b$, then A and B have an uncertain identity potential. If $a \leq b$, then A and B have an uncertain uncertainty potential.

As shown in Figure 1, this article considers the eight sets of points formed by the values of $\overline{M}_3$ and $\overline{M}_5$ in each image as a set pair: (a_1, a_2), (b_1, b_2), (c_1, c_2), (d_1, d_2), (e_1, e_2), (f_1, f_2), (g_1, g_2), (h_1, h_2), where a_1 and a_2 are the three-point and five-point means of image a, respectively, and b_1 and b_2 are the three-point and five-point means of image b, and so on.

As a special case of set pairs, pairs also have similarities, differences, and opposites. Suppose that the values corresponding to the pair of numbers A and B are s and t, and $s \leq t$. s and t represent the difference in the grayscale values of the pixel points [12]. If $t \leq 1$, it means that the grayscale values of the two adjacent points are almost equal, and there is no image edge to detect in this direction, that is, the degree of identity $a = 1$ and the degree of opposition $c = 0$. According to the research in literature by Pu et al. [13], it is easy to know that the proportion of s in the first-order opposite interval [$1/t$,t] of t for a pair (s, t) is:

$$p = \frac{s}{t - \frac{1}{t}} = \frac{st}{t^2 - 1} \tag{2}$$

The degree of opposition between s and t in the [$1/t$,t] is:

$$c = 1 - p = \frac{t^2 - st - 1}{t^2 - 1} \tag{3}$$

The same degree of s and t can get:

$$a = s/t \tag{4}$$

The difference between the pairs of numbers (s, t) is:

$$b = p - a = \frac{st}{t^2 - 1} - \frac{s}{t} = \frac{s}{t(t^2 - 1)} \tag{5}$$

Therefore, the expression of the connection degree of the pair (s, t) in the connection degree situation can be expressed as:

$$\mu = a + bi + cj = \frac{s}{t} + \frac{s}{t(t^2-1)} i + \frac{t^2 - st - 1}{t^2 - 1} j \tag{6}$$

Due to the large difference in pixel values between pixel points along the edge direction of the image, for each point to be detected in the image, the strongest opposite trend in the 9th case can be selected according to the relationship between identity and opposition in Table 2 to determine whether there is an image edge.

3. The Algorithm of Edge Detection

The purpose of image edge detection is to extract the edges of the image and separate different regions so that the internal features or attributes within the same region are consistent or similar, while the internal features or attributes between adjacent regions are different from each other. The edges of objects can be recognized by people because there is a large change in the grayscale value at the edge, which is within a certain range of human eye resolution for color values. Experiments have confirmed that when the grayscale range of the full image is between 0 and 255, if the grayscale difference between adjacent objects is less than 10 levels, it will exceed the human eye's perception ability for grayscale differences, and the human eye cannot distinguish between the two objects [14].

When detecting whether a certain f(x, y) in the input $M \times N$ image f is an edge point, the 8 sets of points formed by the values of $\overline{M}_3$ and $\overline{M}_5$ in each image of the half-neighborhood can be used as set pairs, and Equation (6) can be applied to calculate their opposite degree and identity degree. Then, according to the situational relationship between opposite degree and identity degree in Table 2, it can be determined whether the point to be detected is an edge point of the image.

Based on the fact that the difference in pixel direction between image edges is 10 or more, which can be recognized by the human eye as an edge, and the larger the pixel, the larger the value of Equation (4), which is likely to be greater than 50%. Taking pixels 178 and 188 as examples, the value of Equation (4) is 0.94. Therefore, using a<c to determine the strongest opposing trend will not be suitable for the research environment in this article.

In the experiment, the situation of finding 8 pairs of set pairs that satisfy the 9th situation is changed to finding the maximum c/a of the 8 pairs of set pairs, which means that the direction with the maximum opposite degree c and the minimum identity degree a is considered as the most likely direction of image edges [15]. After finding this possible direction, a threshold is used to determine whether it is a boundary direction. Since standard deviation can reflect the degree of dispersion of a data set, it is considered that the absolute value of the difference between the mean of three points along the edge direction and the mean of five points should not be less than the standard deviation of all points in the 8-neighborhood, and only when the standard deviation is not less than 10 can it be accepted as an edge.

The algorithm is described as follows:

1) First, read the grayscale image, calculate the size of the image, and extract every 3*3 image matrix.
2) For the central pixel point f(x, y) in the matrix, 8 sets of number pairs are formed by (a_1, a_2), (b_1, b_2), (c_1, c_2), (d_1, d_2), (e_1, e_2), (f_1, f_2), (g_1, g_2), (h_1, h_2). Using Equation (6), The connectedness degree $\mu = a + bi + cj$ is calculated for each of them.
3) The obtained 8 sets of contact degrees are processed: the maximum value of the 8 c/a is taken (c/a are not taken if they are equal, and $a < b$ && $b > c$). When the absolute value of the difference between the three-point mean and the five-point mean is greater than or equal to the standard deviation, and the standard deviation is greater than or equal to 10, it is determined to be a marginal point.
4) Repeating steps (1) and (2) completes the edge detection of the image. After completing the edge detection, thin the image with bwmorph (image, 'thin', Inf).

Table 2
Degree connection situation

Serial number	Grade	Set pair potential classification
1	1	Slender balance of power
2	2	Weak balance of power
3	3	Strong balance of power
4	4	Quasi-equilibrium
5	1	Quasi-isostatic potential
6	2	Strong synergy
7	3	Weak synergy
8	4	Weak equipotential
9	1	Quasi-reverse potential
10	2	Strong adverse trend
11	3	Weak adverse potential
12	4	Weak adverse potential
13	1	Uncertain same potential
14	2	Uncertain potential

4. Experimental Result Analysis

In order to verify the feasibility and effectiveness of the application of connection degree in the field of image edge detection, this article uses a simulation example and programming on a PC with Matlab7.0. The simulation results are compared with traditional Sobel algorithm and canny algorithm. Figures 2 and 3 show the segmentation comparison without noise interference. In the figure, set pair analysis is the half-neighborhood image edge detection result based on set pair analysis in Lee and Hung [16]. Figures 4, 5, and 6 show the segmentation comparison results with salt and pepper noise. The comparison of recognition accuracy as shown in Table 3.

From the simulation results, it can be seen that the experimental results are more prominent when using the idea of combining the connection degree situation with the half-neighborhood without adding noise. This is mainly reflected in the better detection of the contours of faces and the left side of high-rise buildings compared to the Sobel algorithm, and the slightly effective removal of grass noise compared to the Canny algorithm [17].

Figure 2
Cameraman without noise

Figure 3
Head CT without noise

salt and pepper image | SPAaddnoise | Sobel processing of pepper and salt image | canny processing of pepper and sait

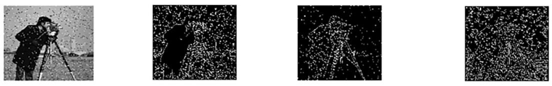


Figure 4
Cameraman with noise

salt and pepper image | SPAaddnoise | Sobel processing of pepper and salt image | canny processing of pepper and salt

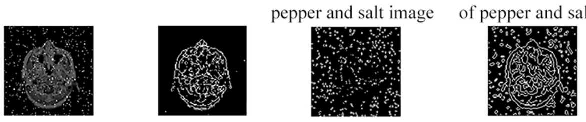


Figure 5
Mira with noise

Original image | SPA | Sobel edge processing | canny edge processing

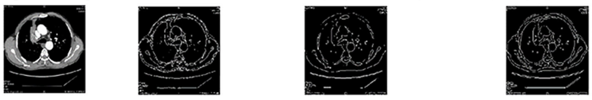


Figure 6
Head CT with noise

salt and pepper image | SPAaddnoise | Sobel processing of pepper and salt image | canny processing of pepper and salt

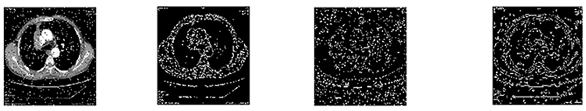


Table 3
Comparison of recognition accuracy

Comparison	Sobel Acc	Canny Acc	SPA Acc
Cameraman without noise	87.60%	88.40%	89.30%
Cameraman with noise	92.10%	92.40%	94.43%
Mira with noise	91.51%	90.23%	92.34%
Head CT without noise	90.87%	93.33%	93.44%
Head CT with noise	93.21%	94.15%	94.28%

In the experiment with the addition of salt and pepper noise, the results of using the combination of connection degree and half-neighborhood are still outstanding, as evidenced by the fact that small objects such as people and houses are not lost, and the visual effect is clearer than that of Sobel and Canny algorithms.

The improved algorithm combining the connection degree situation and half-neighborhood has better edge detection and tumor extraction performance for the other two medical images with noise added than other algorithms [18]. The edge detected by this algorithm is more accurate than the Sobel algorithm without salt and pepper noise added, so the promotion and application of this improved algorithm in the medical field are of great significance.

5. Conclusion

This paper proposes a new algorithm improvement idea in the field of image edge detection based on the idea of half-neighborhood algorithm and using an improved method of relationship degree situation. This improved algorithm not only optimizes the complexity of the current algorithm, but also has better advantages than traditional algorithms in terms of simplicity, anti-interference, improving edge detection accuracy, protecting edge details, and visibility [19]. In addition, the algorithm research proposed in this paper provides a new perspective and has potential value in medical image detection, with broad application prospects. In summary, this paper has made important contributions in theoretical innovation, method improvement, and practical application.

The current edge detection technology algorithms still have certain challenges in processing images containing noise. Although existing algorithms can suppress noise to a certain extent, how to effectively remove noise while maintaining edge detection accuracy remains a key issue in current research. In addition, the edge characteristics in actual images may vary spatially due to physical and lighting factors, so how to design an algorithm that can adaptively detect edge changes in multiple spatial ranges is also an important issue in current research by Monkam et al. [20].

With the continuous development of deep learning technology in the future, edge detection technology is expected to achieve greater breakthroughs. Firstly, deep learning can help algorithms automatically learn and discover edge features in images, thereby improving detection accuracy and efficiency; Secondly, deep learning can also help algorithms better adapt to various complex image environments and improve their generalization ability. Finally, with the rapid development of AI-related technologies, the application scenarios of edge computing will continue to expand, and its application prospects in intelligent manufacturing, smart cities, medical health, and other fields are very broad.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Guohua Ji: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Project administration. **Yachong Tian:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Xianyi Cheng:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Supervision.

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Glossary

Half-neighborhood: In image processing and other fields, it refers to the partially adjacent area of a node or pixel point.

SPA: A systematic analysis method proposed by Chinese scholar Keqin Zhao in 1989.

Image edge detection: It is locating rapid changes in brightness or color to outline objects or regions in an image.