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Sub-pixel detection algorithm based on cubic B-spline curve and multi-scale adaptive wavelet transform

Yuming Chen*, Yongzhi Li, Yingkai Zhao

Nanjing University of Technology, No. 30 Puzhu Road, Nanjing, China

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ABSTRACT

This paper presents a method of sub-pixel image edge detection based on the cubic B-spline curve interpolation and the wavelet transform, to solve the problem that the system has increasing demands to the algorithm in real-time and the accuracy. The high resolution and anti-noise of the multi-scale adaptive threshold wavelet transform are used to test the modulus maxima of the image edge. Using the cubic B-spline curve interpolation, the accurate interpolation and the edge of the image reconstruction can be realized in sub-pixel level when the image edge is irregular. The experimental results indicate that mean squared error in the new method is less than 0.02 pixel. The measure data of the standard deviation is 0.0043 mm. From above on, the proposed method is robust to noise and it has a high-precision positioning. Compared to these popular edge detection algorithms, the proposed method performs better than those algorithms on detail reserving and positioning accuracy.

1. Introduction

In recent years, the measure systems based on image process have widely used. The research hotspot in this field is to improve the accuracy of measurement. Sub-pixel edge detection technology is an importance part of this research. The general edge detection method is based on the differential technology [1], such as Laplacian operator, Sobel operator and Log operator. Their detection accuracy of these methods can just reach pixel level precision. Due to the differential operator is sensitive to noise, some false edges often arise with these methods. With the continuous improvement of the accuracy requirement in the industrial inspection, the traditional edge detection methods have been difficult to achieve the actual requirements. So the sub-pixel edge detection method has attracted extensive attention. There are many sub-pixel edge detection methods [2], such as interpolation method, polynomial fitting, space gray moment method and the least squares estimation method, etc. These methods have their respective advantages and disadvantages with their application scope. The accuracy of the interpolation method is better than the other, and the minimum amount of calculation in all algorithms. To improve the detection precision and overcome that the traditional detection methods are susceptible to noise, We put forward a new method of edge detection, which is two- steps process, firstly the adaptive wavelet transform is used to get the rough edge, because the wavelet transform can highlight the local characteristics in time domain and frequency domain, The high frequency signal is separated from the image with this method, to distinguish the edge and the noise. The way can accurately locate on the edge of the position. And then, in the area of the above method, cubic B-spline interpolation method is used to further improve the accuracy of edge detection [3], and make the precision of edge detection to achieve sub-pixel level. This method has very good denoising performance with sub-pixel level. The proposed method is suitable for field application with good robustness and less restrictions, and has a high application value in high-precision vision measurement for machine parts and traffic monitoring [4].

2. Multi-scale adaptive wavelet transform denoising

If we take wavelet transform with the same threshold to the whole image, local maximum values formed by fine weak edge is filtered with the modulus maximum of the noise generated by the uneven gray level to removed [5]. We propose a multi-scale adaptive threshold method, The following method is used to determine the adaptive threshold, The image is divided into many small pieces, Modulus maxima values in these small pieces would be averaged, If the average value is less than lower limit, The point is considered no edge point, On the contrary, if Modulus value in the point is greater than or equal to the average, the one is treated as the edge,

* Corresponding author. Tel.: +86 013813994307.
E-mail address: njutcym@hotmail.com (Y. Chen).

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Point has been removed, which's modulus value is lower than the average.

Step 1: The original image $f(u, v)$ is generated the module $M_{2j}f(u, v)$ and the phase Angle $A_{2j}f(u, v)$ by the wavelet transform.

Step 2: If the module $M_{2j}f(u, v)$ gets a maximum value in the direction of $A_{2j}f(u, v)$, it shows that the point is belong to the edge, we wipe off the undesirable points and then obtain the rough edge image $p_{2^j(u,v)}$.

Step 3: The rough edge image $p_{2^j(u,v)}$ is scanned by window $n \times n$. According to the formula of adaptive threshold $T = T_0 + A_0 \times \sum_{i,j} C_{i,j}$, in image $p_{2^j(u,v)}$, the point is regarded as the edge point, which's Modulus maxima in the corresponding window is greater than T. Otherwise, the point will be removed.

Step 4: Move scanning window, we scan the rough edge image $p_{2^j(u,v)}$, get the edge point by step (3). Finally, solve all edge points.

Step 5: Repeat steps 1–4, until obtaining the edge image in all scales.

Step 6: Output the edge image in all scales.

3. Subpixel edge with the cubic B-spline curve

Cubic B-spline curve has a good ability of curve expression, has been widely used in the computer graphics, is an important tool for the image interpolation. We apply it to get the sub-pixel image with interpolation [6].$n+1$ control points B-spline curve equation can be defined as the following formula:

$$P(u) = \sum_{j=0}^{n} p_j B_{j,k}(u); \quad u_{k-1} \le u \le u_{n+1} \tag{1}$$

Among, P_j is one of the $n+1$ control points. The range of u depends on the parameter selection of B-spline.

B-spline basis function $B_{j,k}$ is a polynomial with $k-1$ degree, the proposed algorithm employ cubic-B spline, so parameter k is 4. B-spline basis function $B_{j,k}$ is defined by the Cox–de Boor recursion formulas:

$$B_{j,1}(u) = \begin{cases} 1, u_j & \le u \le u_{j+1} \\ 0, & \text{other} \end{cases}$$
$$B_{j,k}(u) = \frac{u - u_j}{u_{j+k-1} - u_j} B_{j,k-1}(u) + \frac{u_{j+k} - u}{u_{j+k} - u_{j+1}} B_{j+1,k-1}(u) \tag{2}$$

For the image, we can regard it as a piece of image grey value as grid control points of B-spline surface. After image magnification, we resample sub-pixel points as the point on the surface, then can achieve sub-pixel image using B-spline surface interpolation method.

$$P(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} p_{i,j} B_{i,4}(u) B_{j,4}(v);$$
$$u_3 \le u \le u_{m+1}, \quad v_3 \le v \le v_{n+1} \tag{3}$$

The proposed method uses the adjacent 25 pixel points in the image as a grid of control points which is constructed as a B-spline surface. In the formula (3), m, n is 4, the grid matrix is $p_{i,j}(i=0, 1, 2, \ldots, m; j=0, 1, 2, \ldots, n)$. Assume that the original image size is $W \times H$, the zoom scale is S_w and S_v, which are any real. Each the pixel location (i, j) in the interpolation image corresponds to position (i_0, j_0) in the original image. Their relationship is $i_0 = i/S_w, j_0 = j/S_v$.

Let $ii = [i_0]$, $jj = [j_0]$, of which $[\bullet]$ is to rounding operation of i_0, j_0, (i_0, j_0) Located in the 25 pixels around (ii, jj) within the grid. So use the interpolation formula (3) can solve function value of (i_0, j_0), then get the grey value of location (i, j) in the enlarged image. In the direction of u and v, the calculated formula (4) is as follows:

$$u = \frac{(i_0 - ii)}{5}, \quad v = \frac{(j_0 - jj)}{5} \tag{4}$$

The interpolation image is more smooth, which is obtained by the B-spline surface. It is visually more clear, there is the sawtooth pattern in the edge area. The noise of the image is increasing and its visual quality is decreasing, which is processed by the Bicubic interpolation algorithm, But its edges are relatively clear, visual effect is good. So the no edge area is processed by the cubic B-spline surface interpolation, the edge area is presented by the Bicubic interpolation.

First of all, distinguish the edge points. Given a set of pixels value $P = \{f(i, j), i = 0, 1, \ldots, m; j = 0, 1, \ldots, n\}$ in the original image, introduce parameter A:

$$A = \left| f(i, j) - f(i+1, j+1) \right| + \left| f(i+1, j), f(i, j+1) \right| \tag{5}$$

Set threshold A_0, if $A > A_0$, $f(i, j)$ is the edge point, not vice versa. According to the formula (5), we determine whether point (i, j) is belong to the edge area. If so, we get gray value $f(i, j)$ at the point (i, j) with the Bicubic interpolation algorithm. On the basis of formula (6), we take advantage of the gray value $f(i, j)$ of the 16 pixel around point (i_0, j_0),

$$f(i_0, j_0) = \sum w_x w_y f(x, y) \tag{6}$$

Among (x, y) denote pixel coordinates, w_x is the weighted value of Interpolation in the horizontal axis, w_y is the weighted one in the vertical coordinates. Its respective formula is as follows:

$$w_x = \begin{cases} 1 - 2d_x^2 + 3d_x^3 & d_x < 1 \\ 4 - 8d_x + 5d_x^2 - d_x^3 & d_x > 1 \end{cases}, \quad d_x = x - i_0$$
$$w_y = \begin{cases} 1 - 2d_y^2 + 3d_y^3 & d_y < 1 \\ 4 - 8d_y + 5d_y^2 - d_y^3 & d_y > 1 \end{cases}, \quad d_y = y - j_0 \tag{7}$$

So we get the accurate edge of the image. In this paper, the proposed algorithm has good ability against image noise, can detect the edge of the weaker characteristics, so as to completely express the characteristics of the image. The processed image has the clearest edges.

4. Experiment result

We select the image about road with Gaussian noises to be the original image. Do edge detection using traditional edge detection algorithms and the proposed method, list the edge detection results. The result is show in Fig. 1.

Log operator: First, do image filtering with a Gaussian function, and then do Laplacian transform with filtered image, consider the point correspond to zero is the boundary point. It may smooth out the original sharp edge while suppressing noise. It is necessary to select the appropriate variance parameter of Gaussian function to get the best image processing effect.

Canny subpixel operator: This operator uses a dual-threshold method to detect and connect edge, this method is less susceptible to noise and is ability to detect weak edge, but the continuity of the boundary is worse than Log operator. From the simulation result, all of these traditional operators have the problem of error detection or missing detection. The detection accuracy cannot achieve requirements really or technically.

The proposed operator: The proposed method gets the detection results at different scales by making the best of the scale characteristic of wavelet transform. The new method can eliminate image noise and detect the edge details effectively. In addition, it has good accuracy. We can get the optimal edge detection result with the