Coarse-to-Fine Sub-pixel Edge Localization for Dimensional Measurement Based on Radial Basis Function

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This paper has introduced a novel coarse-to-fine subpixel edge localization method based on radial basis function interpolation (RBFI). In the paper the computational algorithm and processing steps of the RBFI subpixel edge localization technique are detailed. The important performances of the subpixel localization ability, such as resolution, edge positioning variation with edge orientation, real edge location accuracy are investigated compared with the typical edge localization techniques, such as Canny detector, Zernik moment techniques, Gaussian fitting techniques. A precision experiment of measuring a standard adjustable gauge by a 2D image measurement machine has been carried out to verify the RBFI technique performances. The research investigation shows that the RBFI technique has the orientation invariant feature and the localization resolution is higher than Zernik moment techniques and Gaussian fitting techniques.

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1. Introduction

Subpixel edge localization is very crucial to dimensional measurement in machine vision technology and has attracted more and more attention. There have been many algorithms of subpixel edge detection developed. Most of subpixel edge localization methods are derived from the numerical approximation theory, where the subpixel positioning of an edge is achieved by modeling the image edge with its neighborhood pixels and then to solve the relevant parameters. The localization methods can be categorized into the following three categories: reconstruction techniques, interpolation techniques, moment-based techniques[1]. Reconstruction techniques are to reconstruct the continuous gradient or grey level profile from the discrete signal obtained at the end of the coarse detection by projecting onto a set of basis functions. The basis functions include splines[2], Gaussian functions, sinc functions, Chebyshev polynomials, etc. Interpolation techniques to approximate the grey level or gradient profile of the edge in the vicinity of the maxima (coarse edge location) using some interpolating functions like polynomials and Gaussians[3]. Moment-based techniques use the edge gradient statistical measures such as the gray-level moments, spatial moments, centroid values, local energy values, expectation values, etc, to obtain the an idealized sub-pixel precision edge[4]. A comprehensive investigation of sub-pixel edge detection schemes in metrology can be referred to the reference [1].

In the techniques above, the most popular approaches are interpolation techniques implemented in the neighborhood of the coarse edge location using a suitable model. Considering the fact that radial basis function (RBF) is one of the primary tools for interpolating multidimensional scattered data, due to its ability to handle arbitrarily scattered data, easily generalize to several space dimensions and to provide spectral accuracy, and widely used in cartography, neural networks, medical imaging and the numerical solution of partial differential equations[5], in the following sections the paper will introduce a novel coarse-to-fine subpixel edge localization method with better properties based on radial basis function interpolation (RBFI). The important properties of some typical subpixel localizations, such as resolution, edge positioning variation with edge orientation, definitions of real edge are investigated compared with the edge localization techniques of Canny (pixel resolution), Zernik moment, Gauss fitting methods. The experimental results show that the resolution of RBFI subpixel edge localization is higher than the Zernik moment method, which has been acknowledged with higher resolution than many traditional methods. The edge position defined by RBFI subpixel edge localization also keeps constant with the curve slop variations.

2. Steps of subpixel edge localization

Almost all subpixel edge localization techniques surveyed in the last sections follow coarse-to-fine two-step processes[1]:

(1) Coarse detection. In the coarse detection process, discrete

filters, such as the Canny, Sobel, and Shen-Castan gradient filters, etc, are used to obtain gradient local maxima to localize edge at pixel level.

(2) Sub-pixel localization. The process is to refine edge location to obtain sub-pixel resolution. In the process, an objective function with transformation parameters is constructed only in the vicinity of the detected coarse edge to reduce the computational load, and then minimized to realize sub-pixel localization.

In our RBFI method, the coarse detection is implemented by Canny filter and sub-pixel localization by a kind of radial basis function. RBF interpolation is carried out in one dimensional space to reduce computational load. Thus, the RBFI subpixel edge location technique can be summarized in following steps.

Step 1: The pixel level edge position is coarsely detected by Canny method.

Step 2: Then the normal direction of each point at the Canny edge is computed.

Step 3: The neighborhood pixels along the normal direction at the point is chosen

Step 4: The neighborhood pixels are interpolated by a radial basis function in the normal direction.

Step 5: The subpixel edge is estimated based on the curve of the radial basis function.

3. Subpixel edge definition

Before localizing a subpixel edge using the RBFI algorithm, the most important thing is to model the edge, investigate where the real edge is and give a subpixel edge definition. As shown in Fig.1, there are verity of edges, including in particular the sudden step edge (a), the slanted step edge (b), the smooth step edge(c), the planar edge (d), the roof edge (e), the line edge (f) and various intermediate edge profiles[6]. A real edge is often contaminated by noises and have a complicated profiles as shown in Fig.1(g).

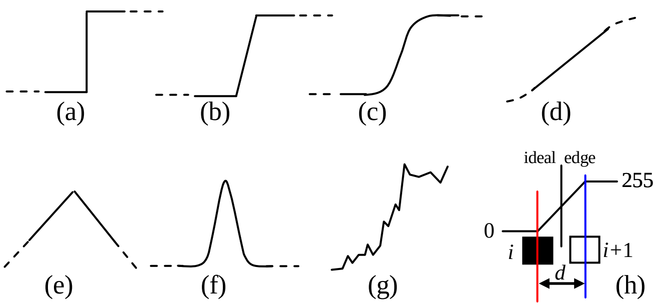


Fig.1 Edge models

In the above edge models, the sudden step edge has frequently been used as a paradigm with which to investigate and test the performance of edge localization. An edge is defined by a discontinuity in gray level values. In digital image, an edge may be digitalized by two pixels, which means the real edge may locate between the black and white pixels. But the problem is where to find the real edge and how to define the ideal edge shown in the sudden step edge profile. In Fig.1 (h), there are three possible positions of the real edge. One is at the dark pixel position, another at white pixel position and the third at the middle place of the two pixels. If defining the edge position is at ether position of dark or white pixels, a pixel distance error is probably induced. Maybe the ideal way is to define the ideal edge is at the middle place of the two pixels. Thus the edge localization has half pixel accuracy.

4. RBFI subpixel edge localization

4.1 Preprocessing of the edge localization

The RBFI algorithm is illustrated in Fig.2, where a local edge curve is detected by Canny edge detector. Assume there is a pixel point $P(i, j)$ on the coarse edge. In the vicinity of the point, a local edge curve can be fitted by the following quadric polynomial

$$y = ax^2 + bx + c \tag{1}$$

Then the normal line going through the point is obtained. In order to determine the subpixel edge position at the point $P(i, j)$, four rows of pixels evenly distributed up and down at the point and close to the normal, which are …, $P(i\text{-}2, j\text{+}2)$, $P(i\text{-}2, j\text{+}1)$, $P(i\text{-}1, j\text{+}1)$, $P(i\text{-}1, j)$, $P(i,j)$, $P(i\text{+}1, j)$, $P(i\text{+}1, j\text{-}1)$, $P(i\text{+}2, j\text{-}1)$, $P(i\text{+}2, j\text{-}2)$, …, are projected on the normal line. The grey values of the fourteen projected points are approximated to be equal to the values of the corresponding points. The coordinates of the fourteen projected points, $d_{P(i+m, j+n)}$, where m and $n = -2, \cdots, +2$, are obtained by calculating the distances of the projected points to the central point $P(i,j)$. the signs of the points d_P are positive if they are outside the curve and negative inside the local curve. Then the fourteen points are interpolated by the following radial basis function.

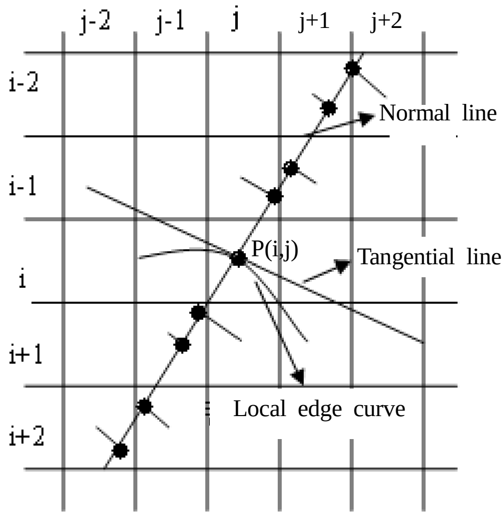


Fig.2 RBFI algorithm illustration

4.2 RBFI algorithm

In subpixel edge localization, a multiquadric radial basis function is chosen to interpolate the projected points on the normal line. The multiquadric function is defined as[7]

$$\phi_i(r) = \sqrt{r^2 + c_i^2}, i = 0,1,...,n \tag{2}$$

$\phi_i(r)$ has the same asymptotic behavior as r, but is smooth and is infinitely differentiable. c_i is a scale parameter which controls the smoothness of the function. In fact, c_i is the radius of curvature at $r = 0$. For any given curve the c_i can be assumed to be all the same. Then the edge section cut by the plane that goes through the normal line and is perpendicular to the page plane is interpolated by the curve

$$S(x) = \sum_{i=0}^{n} \alpha_i \varphi_i(x) \tag{3}$$

where the radial function $\phi(x)$ is defined as

$$\phi_i(x) = \sqrt{(x - x_i)^2 + c^2}, \quad i = 0,1,\ldots,n \tag{4}$$

The α_i are the solutions of the following simultaneous equations:

$$S(x_k) = \sum_{i=0}^{n} a_i \phi_i(x_k) = f_k, \quad i = 0,1,\ldots,n \tag{5}$$

That is

$$\begin{bmatrix} \phi_0(x_0) & \phi_1(x_0) & \ldots\ldots & \phi_n(x_0) \\ \phi_0(x_1) & \phi_1(x_1) & & \phi_n(x_1) \\ \ldots & \ldots & \ldots & \ldots \\ \phi_0(x_n) & \phi_1(x_n) & \ldots & \phi_n(x_n) \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \ldots \\ a_n \end{bmatrix} = \begin{bmatrix} f_0 \\ f_1 \\ \ldots \\ f_n \end{bmatrix} \tag{6}$$

After the a_i are solved, the error function indicated by Eqn.7 can be used by substituting the a_i into the Eqn.5, to judge if the scale parameter value is optimal and the interpolated curve is reasonable. Then the sub-pixel edge position is approximately localized at the middle of the slop part of the interpolated curve.

$$W(x) = S(x) - f(x) \tag{7}$$

5. Comparisons of RBFI Performances

A good edge localization algorithm should be robust to noises and is orientation invariant. That means the edge localization is not influenced by the edge normal angele. To compare the RBFI performances with other edge techniques, such as Canny edge detector, Gaussian fitting technique,Zernike moment[8],the circle edge localization of the two circle hole images shown in Fig.3(a) and (b) are implemented by different edge localization techniques in 8 directions shown in Fig.3(c). The edge localization results are illustrated in Fig.3(d) to (k). The sudden step edges presented by Fig.3(d).(e),(f) and (g) are the edge profiles of the white black hole image shown in Fig.3(a) in direction 0, 45, 90 and 180 degree respectively, and the Fig.3(h).(i),(j) and (k) indicate the edge profiles of real circle hole image in the directions. Note that the two points *w* and *k* in Fig.3(d) are the two adjacent white and black pixels. The position indicated by the vertical green line is obtained by RBFI algorithm. The positions at the red vertical lines are calculated by Gaussian fitting technique, the positions at blue vertical lines by Zernike moment technique and the positions at black dot lines by Canny detector. These experimental results illustrate that Canny edge detector has pixel resolution, Zernike moment and Gaussian fitting technique are orientation variant, though the two techniques has subpixel resolution. The positions between the two adjacent points *w* and *k* on the edge profiles located by Zernike moment and Gaussian fitting technique are changed with the normal directions of the edges. The RBFI algorithm has excellent performance in subpixel localization. The position determined by the RBFI algorithm is always in the middle of the two adjacent pixels wherever the normal directions are.

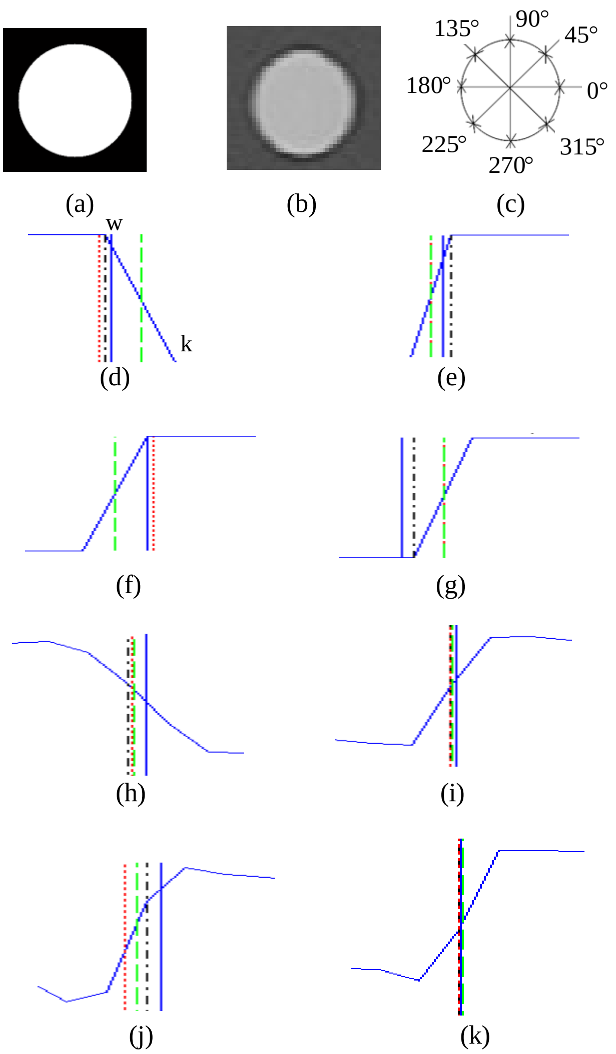


Fig.3 Investigating the performances of the edge localization algorithms

6. Precision experimental verification

To verify the performance of the RBFI subpixel edge localization algorithm further, the following precision measurement experiments have been carried out. In the experiments, a standard adjustable gauge produced by the micrometer shown in Fig.4 was measured by a 2D image measurement machine. The clearance gauge was decreased in every 2 μm and then images shown in Fig.5(a) was taken. In the experiment, total 10 images were grabbed and the edge localizations shown in Fig.5 (b), (c) and (d) were calculated by Zernike moment , Gaussian fitting technique and RBFI algorithm respectively. The 2D image measurement machine was carefully calibrated and the pixel scale factor is k = 11.1111 $\mu\text{m/pixel}$. Then the image measurement accuracy and edge localization resolution can be evaluated. The calculation results are illustrated in Fig.6.

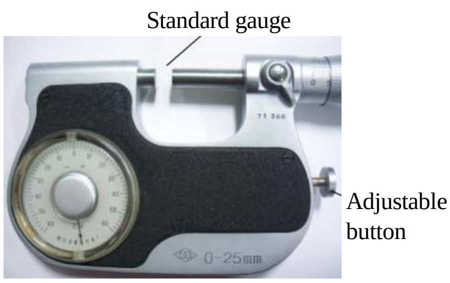


Fig.4 Micrometer gauge measurement

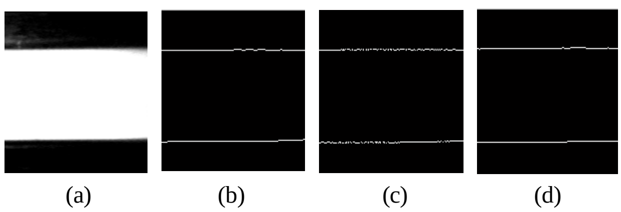
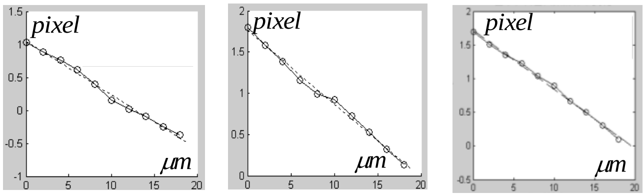


Fig.5 The gauge image and edge localization results

In Fig.6, the vertical axis denotes pixels and horizontal axis denotes the clearance gauge in μm unit. The average measurement error of each clearance gauge calculated by Zernike moment, Gaussian fitting technique and RBFI algorithm respectively are -4.63 μm, 2.55 μm and 2.21 μm. The experimental results present that the RBFI algorithm has better performance than other two techniques. The Zernike moment is the worst. Our other experiments also showed that Zernike moment technique has worst performance in subpixel localization when the edge is at horizontal direction. That is the reason why the measurement error produced by Zernike moment technique is two times bigger than others.



(a) Zernike moment (b) Gaussian fitting (c) RBFI algorithm

Fig.6 The resolution of edge localization

The Table 1 lists the fitting results of the 10 clearance gauge localizations determined by Zernike moment, Gaussian fitting technique and RBFI algorithm respectively. The third column is the average perpendicular distance of the ten positions against to the fitting lines, which indicates the geometrical errors of the image measurement by different subpixel localization techniques. The fourth column shows the standard derivations. The table also verifies that the RBFI algorithm proposed in this paper has better performance. The subpixel resolution can reach about 0.2 pixel.

algorithms	slop (pixel/μm)	*Ave* (pixel)	σ (pixel)
Zernike	−0.0815	0.0307	0.0291
Gaussian	−0.0893	0.0271	0.0197
RBFI	−0.0897	0.0252	0.0002

Table 1 algorithm performance evaluation

4. Summary

This paper has introduced a novel coarse-to-fine subpixel edge localization method based on radial basis function interpolation (RBFI). The algorithm and steps of the subpixel edge localization is depicted. The important performances of subpixel localization ability, such as resolution, edge positioning variation with edge orientation, definitions of real edge are investigated compared with the typical edge localization techniques, Canny detector, Zernik moment techniques, Gaussian fitting techniques. A precision measurement experiment has been carried out to verify the performance of the RBFI subpixel edge localization algorithm. In the experiment a standard adjustable gauge produced by the micrometer was measured by a 2D image measurement machine. The two side edge positions of the adjustable clearance gauge in images are located by the RBFI subpixel edge localization algorithm. the localization performances are compared with that of Zernik moment techniques, Gaussian fitting techniques. The investigation shows that resolution of RBFI subpixel edge localization is higher than other techniques. The edge position defined by RBFI edge localization also keeps constant with the curve slop. That means the RBFT has the orientation invariant feature.

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