AUTOMATIC EDGE DETECTION IN NOISY FRINGE PATTERNS: A PRACTICAL APPROACH

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Abstract.   Fringe patterns are usually analyzed using a predefined window due to the difficulty associated with finding their edges. This is because, the fringes usually have minimum intensities similar to that of the background and it is difficult to determine where a fringe starts or ends. The presence of the fringes can therefore lead to errors in detecting the edges of the object when using existing edge detection techniques. This paper presents a practical approach towards the automatic detection of the edges of a noisy fringe pattern having different noise levels. The technique uses the dilation and erosion morphological operators combined with a simple neighborhood binary edge detector. The threshold required for the binarization operation is determined from a linear relationship between the threshold value and the standard deviation of Gaussian noise from a simulation study. The proposed technique has been successfully applied to fringe patterns on real objects obtained using the fringe projection method. Some of the limitations of the technique are discussed.

Keywords: Edge detection, fringe patterns

Abstrak.   Corak-corak pinggir biasanya dikaji dengan menggunakan tingkap yang ditakrifkan awal kerana kesukaran mencari sempadannya. Hal ini berlaku kerana pinggir-pinggir tersebut biasanya mempunyai keamatan minimum yang serupa dengan keamatan latar belakang dan adalah sukar untuk menentukan di mana sesuatu pinggir bermula atau berakhir. Kehadiran pinggir-pinggir boleh menyebabkan ralat dalam pengesanan sempadan dengan menggunakan kaedah-kaedah pengesanan sempadan yang sedia ada. Kertas kerja ini membentangkan suatu pendekatan praktik ke arah pengesanan automatik sempadan corak pinggir berhingar dengan paras hingar yang berbeza. Teknik tersebut menggunakan operasi-operasi morfologi pengembangan dan penghakisan serta pengesan sempadan binari kejiranan mudah. Nilai ambang yang diperlukan dalam operasi binarisasi ditentukan daripada hubungkait linear antara nilai ambang dengan sisihan piawai hingar Gaussian daripada kajian simulasi. Teknik tersebut kemudian dilaksanakan dengan jayanya pada corak-corak pinggir pada beberapa objek sebenar yang didapati melalui kaedah pengunjuran pinggir. Beberapa kelemahan kaedah tersebut dibincangkan.

Kata Kunci: Pengesanan sempadan, corak pinggir

1.0   INTRODUCTION

Fringe patterns (interferograms) produced by the various optical techniques such as holographic interferometry, moiré and fringe projection are used widely in the measurement of shapes, displacement and strain [1-4]. The fringe patterns are usually

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analyzed automatically, and one common technique is by using the phase-shift method [5-6]. The advantages of the phase-shift method are the possibility of interpolating between fringes to a high degree of accuracy (up to $1/100^{th}$ of a fringe spacing) and the ability to operate on noisy fringe patterns, such as those obtained from speckle interferometry. The limitations of the technique are due to errors introduced by the phase-shifting process and the need to record, usually, three or more fringe patterns. In applications involving fringe patterns having high fringe densities, good degree of accuracy can still be obtained without using the phase-shift method. In previous work [7], it was shown that when fringe centers were traced and digitized individually, good agreement between theoretical and experimental results can be obtained due to the high fringe orders. Therefore, the technique of tracking fringe centers is still applicable in situations where very high precision measurement is not necessary and large fringe orders are involved in the analysis. In addition, this approach results in a saving in the cost of the experimental design because a precision phase-shifting mechanism is not needed. In addition, only one image is required for the analysis, thus saving computational time.

Automatic tracking of fringe centers was actively researched in the early to mid-eighties [8,9]. One main problem in automatic fringe tracking is to locate the start and end points of a dark fringe on the object surface without the user intervention. This problem arises because fringes usually have minimum intensities similar to that of the background and it is often difficult to determine where a fringe starts or ends. In most cases of automatic analysis, this problem is solved by using a windowing technique [10,11] to segment the area of interest prior to the analysis. The windows used are normally rectangular in shape but in some special applications circular or elliptical windows may be more appropriate. For objects whose shapes are not similar to the shape of the window, the windowing technique often results in the exclusion of areas that are part of the object under investigation, thus making it impossible to extract information from areas outside the window. In order to analyze the entire surface of the object it is therefore necessary to detect the edge of the object from the fringe pattern image completely.

The automatic detection of the edges of complex shapes covered with fringes can be difficult because a normal edge detection algorithm, such as gradient-based operators, e.g. Sobel, Prewitt or Roberts operators [12], will be confused by the presence of fringes. One approach to overcome this problem is to apply heavy low-pass filtering to blur out the fringes and then to detect the edge by differentiating the intensity values in the image or simply by applying a threshold. This approach will, however, be difficult due to the blurring of the edges. With poorly illuminated objects, application of a threshold will not guarantee satisfactory result. An alternative solution is to capture an image of the object in the absence of fringes, trace the boundary and superimpose the boundary onto the object covered with fringes. A similar technique using the edge relaxation method for detecting the edges was used

by Jie-Lin et. al. [13] for finding the edges in a phase map. Although this approach is much simpler it requires an additional image for each surface under investigation. Once the edge of the object in the fringe pattern is detected it is then possible to use a simple fringe tracking algorithm to locate the fringe centers over the entire surface of the object under investigation and not just within a pre-defined window of fixed geometry.

In this paper, a practical approach towards the automatic detection of the edges of noisy fringe patterns having different noise levels is proposed. The standard deviation of noise in the image, σ, was determined from outside the object area in the fringe pattern image. The threshold, t, required for binarization was evaluated from σ using the relationship between σ and t established from analysis carried on computer generated (i.e. simulated) noisy fringe patterns. The edge detection technique was tested on simulated noisy fringe patterns of arbitrary geometry and finally applied to fringe patterns of real objects obtained using the fringe projection method.

2.0 THEORY

In this section, the morphology involved in the proposed technique of detecting edges of a fringe pattern is briefly outlined. The reader is referred to the literature [14,15] for a detailed treatment of these subjects.

The technique of edge detection suitable for fringe patterns proposed in the current work uses the erosion and dilation morphological operators. These two operations form the most fundamental morphological operations and almost all other morphological operations can be derived from these two. Erosion of set A by structuring element B is denoted by $A\Theta B^t$ and is defined mathematically as [15]

$$A\Theta B^t = \{p\,|\,B_p \subset A\} \tag{1}$$

where $\qquad B^t$ is the transpose form of the structuring element set and
$\qquad\qquad B_p$ represents the structuring element centered at point p.

If the structuring element has rotational symmetry, then $A\Theta B^t = A\Theta B$. In binary erosion, this operation can be conceived as the output set obtained where the structuring element or template is completely contained by the image set. In another sense, if any of the pixels defined by the structuring element is set to 0, the output pixel is set to 0. In grayscale erosion the value of the output pixel is the minimum value of all the pixels in the input pixel's neighborhood defined by the structuring element.

Dilation is the 'dual' of erosion, that is, the dilation of a set A is equivalent to the erosion of the complement of set A denoted by A^*. Therefore, dilation which is denoted by $A \oplus B^t$ is defined as [15]

$$A \oplus B^t = A^* \Theta B \tag{2}$$

The mathematical notation of duality means that the dilation can be performed by eroding the complement set by the same structuring element. This means that a foreground object in a binary image can be dilated by eroding the background using the same structuring element. An alternative mathematical definition for dilation is given by [15]

$$A \oplus B^t = \{p \,|\, B_p \cap A \neq 0\} \tag{3}$$

In binary dilation this means that an output pixel will be written at all points where the translated structuring element have a non-empty intersection. In another sense, if any of the pixels defined by the structuring element is set to the value 1, the output pixel is set to 1. In grayscale dilation the value of the output pixel is the maximum value of all the pixels in the input pixel's neighborhood.

A simple method to obtain an 'edge' image from a gray scale image is by taking the difference between the original image and its dilated or eroded image [16]. This may be preceded by preprocessing or followed by postprocessing. The edge image E is then represented by either

$$E = |(A \oplus B^t) - A| \tag{4}$$

or

$$E = |A - (A \ominus B^t)| \tag{5}$$

This method is used in the current work to obtain an intermediate 'edge' image mainly due to its simplicity and the necessary post-processing operations involved.

3.0   SIMULATION STUDY

The algorithm developed for detecting the edges of noisy fringe patterns consists of the following stages:

(i)   filtering using an average filter,
(ii)   grayscale dilation performed twice using a 3×3 structuring element,
(iii)   subtraction of the filtered image in (i) from the dilated image in (ii),
(iv)   binarization using a predefined threshold t,
(v)   first binary erosion using a 3×3 structuring element,
(vi)   binary dilation performed n times,
(vii)   second binary erosion performed $n + 1$ times to return the image to its original size,
(viii) binary edge detection.

The first three stages were used to obtain the 'edge' image. Filtering in stage (i) is applied to the noisy images to remove the high frequency noise. This was done by convolving the image with a 5×5 average filter. This was followed by dilating the

image twice using grayscale dilation with a 3×3 square structuring element (stage (ii)). Similar results can also be arrived at by dilating the image once using a 5×5 structuring element. Next, an edge image was obtained by subtracting the original image from the dilated image in stage (ii). The edge image was then binarized in stage (iv) using a predefined value of threshold t. The value of t was determined by observing the background after stage (vii) as described in the next paragraph. This was followed by a binary erosion operation to suppress the background noise pixels (stage (v)). The image was then dilated a number of times using a 3×3 structuring element in stage (vi). The number of dilations n was determined by observing the output after stage (vii). If any blobs of white pixels remain outside the object area after stage (vii) of the operation, the number of dilations n is increased. This dilation operation is followed by an erosion operation carried out $(n + 1)$ times. A simple binary neighborhood edge detector was used in stage (viii) to finally detect the required boundary. The various stages of processing is illustrated in the flowchart shown in Figure 1. The first seven operations were implemented using the *Matrox* image processing libraries, whereas a simple neighborhood binary edge detector was used in the final stage. The various stages of processing were implemented in a *Visual C++* program with an execution time of approximately three seconds on a 600 MHz Pentium PC. Figure 2(*a*)–(*h*) show the various stages of the proposed edge detection algorithm applied to a noisy simulated fringe pattern. The detected edge is shown in Fig. 2(*h*).

The algorithm shown in Figure 1 is not fully automatic because it requires user intervention. This is due to the fact that the value of threshold t used in the binarization process (stage (iv)) is determined by visually evaluating the final result after stage (vii). If there are error pixels outside the object area then t must be increased and the analysis repeated. Besides t, two other variables affect the accuracy of the detection, that is number of binary dilations n in stage (vi) and the standard deviation of Gaussian noise σ in the image. In order to investigate the effect of σ on the accuracy of the edge detection, n and t were fixed at 10 and 20, respectively, based on preliminary investigation, and the detection error versus standard deviation of noise was determined in repeated analyses using simulated images similar to that shown in Figure 2(*a*). The detection error was represented by the ratio of white-to-black pixels remaining when the segmented areas (e.g. Figure 2(*g*)) from noisy and noise-free images were subtracted pixel-by-pixel. The subtracted images representing the error for standard deviation of noise $\sigma = 14.4$, $\sigma = 17.0$ and $\sigma = 19.4$ gray levels are shown in Figures 3(*a*)–(*c*) respectively. The detection error, as shown in Figure 4, was found to increase rapidly when σ was increased beyond a gray value of 19.

In order to develop a fully automatic technique for finding edges of noisy fringe patterns, independent of the noise standard deviation, it is necessary to establish a relationship between σ and the other variables affecting the detection accuracy. In this investigation, n was fixed at 10 and the relationship between σ and t was deter-
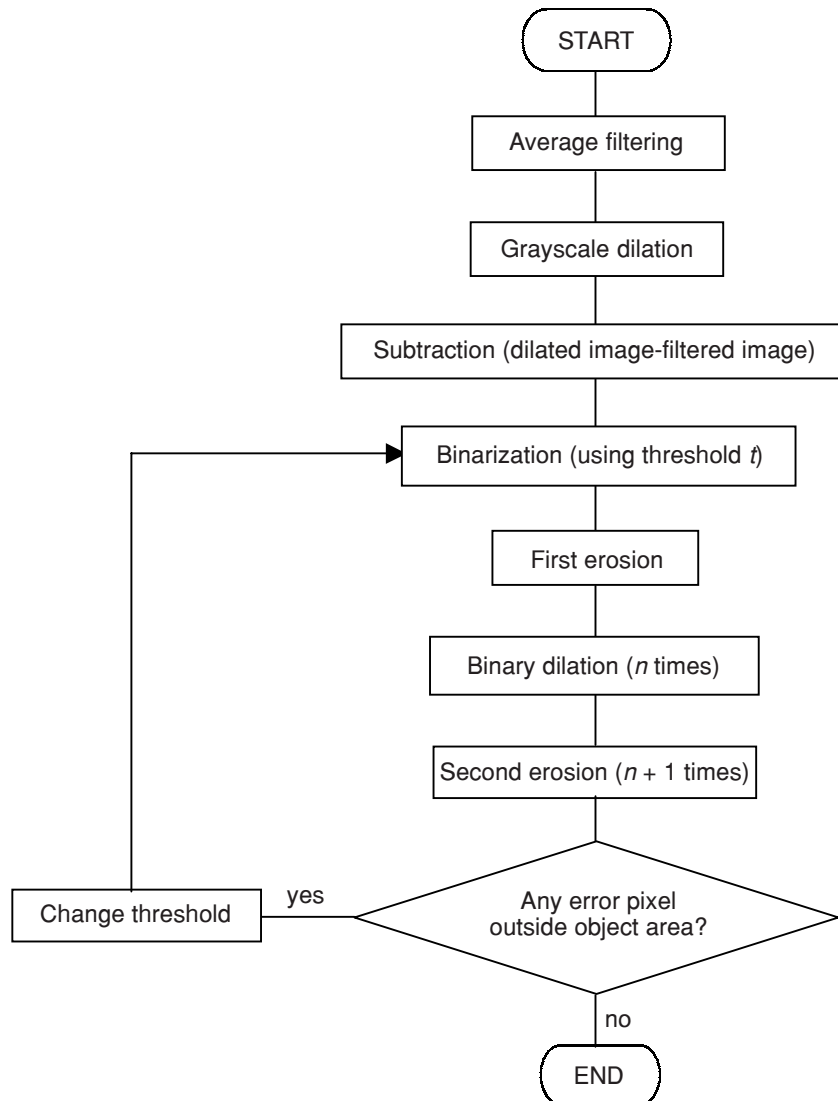
Figure 1   Flowchart of edge detection algorithm

mined by varying t for different values of σ and repeating the analysis on the simulated noisy fringe patterns. It is necessary to fix n because t depends both on σ and n. In actual fact, the value of n depends on the relative size of the object and the overall dimensions of the image. A value of $n = 10$ was selected based on some preliminary work. The relationship between σ and t is shown in Figure 5.

Figure 5 shows that the relationship between the threshold for binarization and standard deviation of noise is approximately linear. In the proposed automatic edge detection process, the value of σ was first evaluated automatically from a predefined square path located at 10 pixels from the border of the image, i.e. in the back-
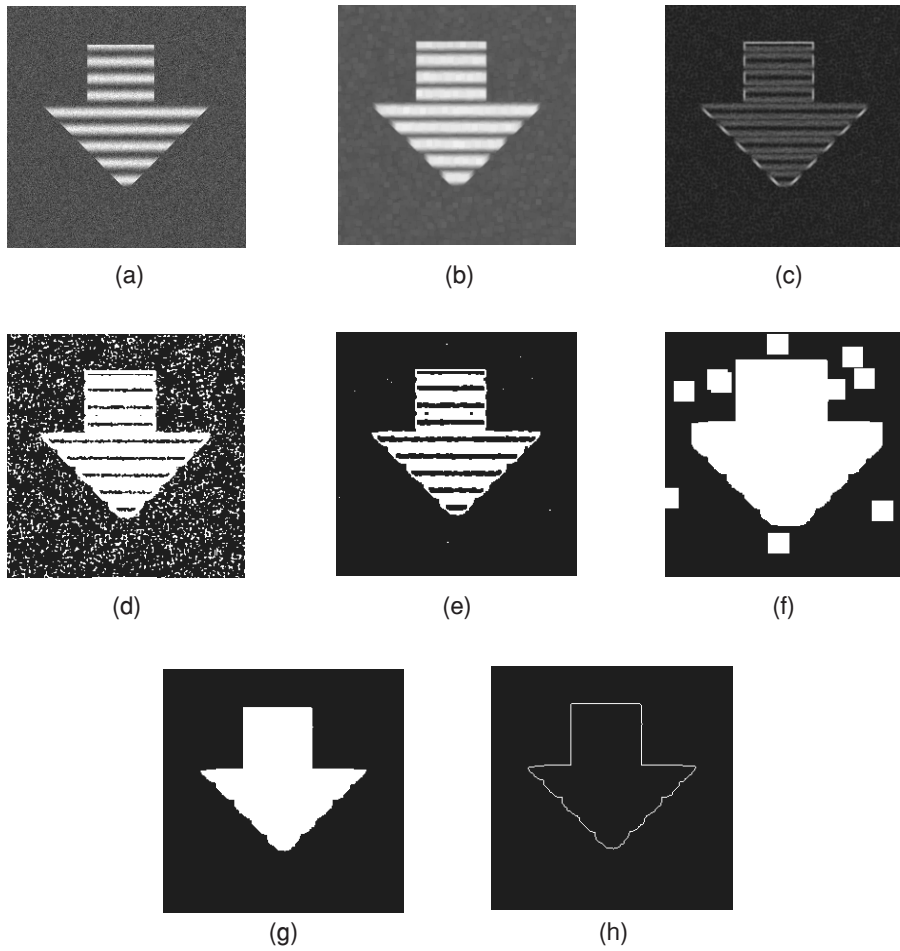
Figure 2 (a) Original noisy fringe pattern, (b) after grayscale dilation, (c) after subtraction, (d) after binarization, (e) after first binary erosion, (f) after binary dilation, (g) after second binary erosion, (h) after binary edge detection
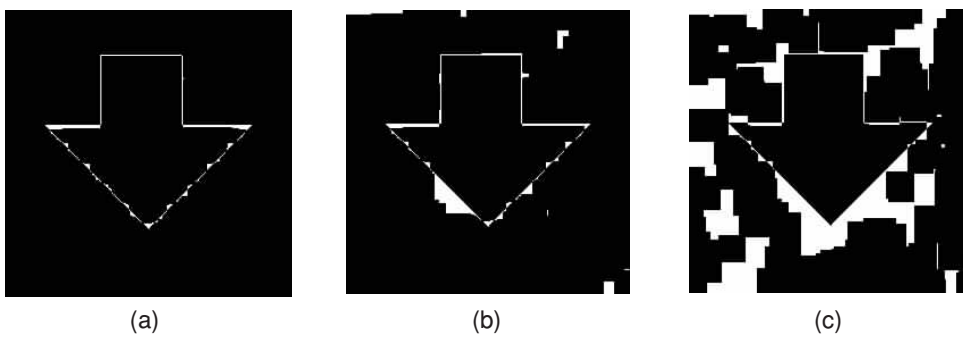

Figure 3 Subtracted images representing detection error for (a) $\sigma = 14.4$, (b) $\sigma = 17.0$ and (c) $\sigma = 19.4$ gray levels
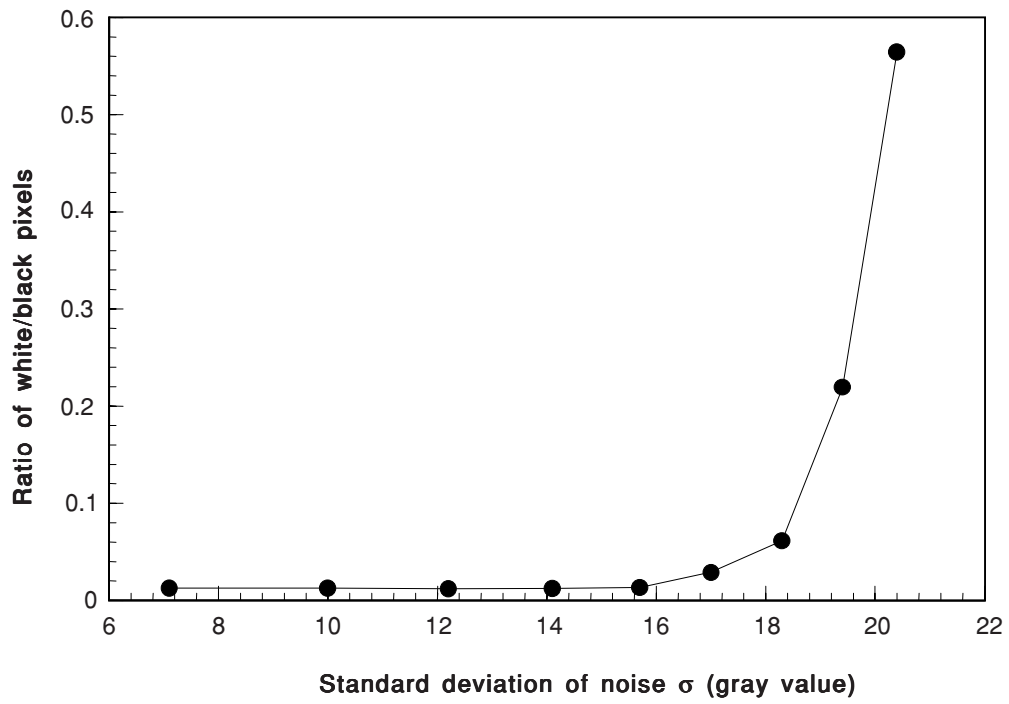
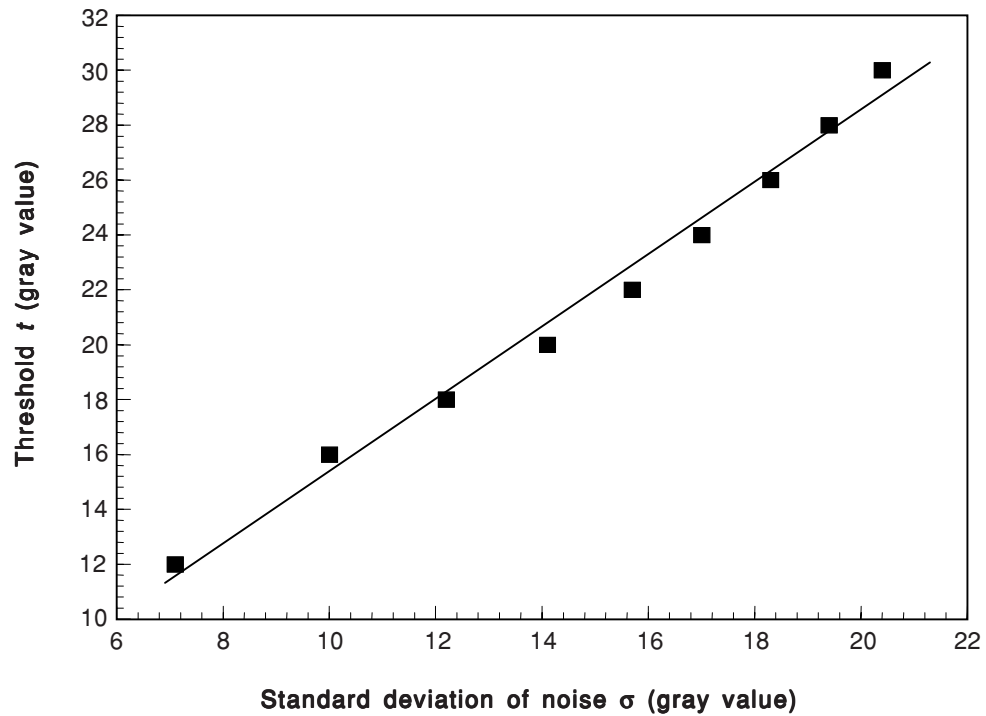**Figure 4**   Effect of σ on detection error

Figure 5   Variation of t with σ

ground. The value of t was then determined from the following linear relationship derived from Figure 5,

$$t = 1.34\sigma + 2.27 \qquad (6)$$

The automatic edge detection was successfully applied to a simulated fringe pattern having $\sigma = 25.4$ as shown in Figure 6(a)–(b) and to a simulated fringe pattern of arbitrary shape having the same σ (Figure 6(c)–(d)). Figure 6(a)–(d) shows that the detection has been carried out successfully although the noise level has been increased to a value outside the range used to establish the linear relationship given by equation (6). The detection error for the fringe patterns in Figures 6(a) and 6(c) was evaluated similarly as before, i.e. by subtracting the segmented areas from noisy and noise-free images (after stage (vii) of the processing). The ratio of white-to-black pixels which represents the detection error was found to be only 0.0138 and 0.0134, respectively, in spite of the increased noise level. To test the robustness of the automatic edge detection technique, the standard deviation of Gaussian noise σ was increased to a high value of 33.6 and the detection error (ratio of white/black pixels)
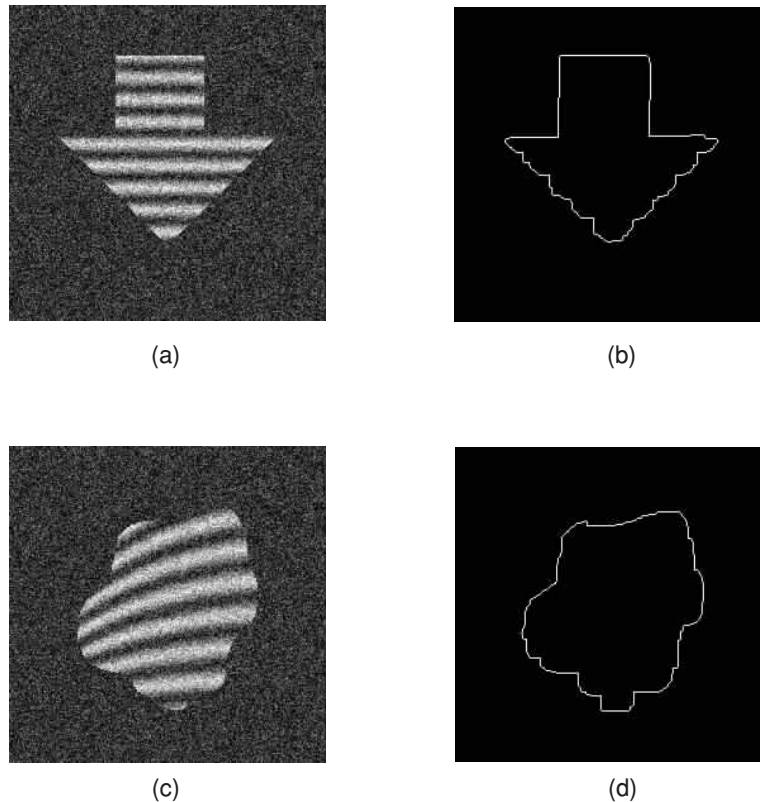

(a)   (b)

(c)   (d)

Figure 6   Edge detection in simulated fringe patterns with $\sigma = 25.4$: (a) Raw fringe pattern of arrow, (b) edge detected from (a), (c) raw fringe pattern of arbitrary shape, (d) edge detected from (c)

was found to be 0.0173. Since the standard deviation of Gaussian noise in real fringe patterns is much lower that 33.6 (see the next section), the proposed method of edge detection in fringe patterns is considered to be sufficiently robust for practical applications.

4.0   APPLICATION TO REAL IMAGES

The automatic detection method developed based on simulated images was applied to fringe patterns of real objects obtained using the fringe projection method. The simulated images used previously were generated based on the following interferometry relation representing a sinusoidal intensity profile:

$$I = A + B \cos \phi \tag{7}$$

where I is the pixel intensity (gray value), A is the uniform background intensity, B is the amplitude of intensity fluctuation and ϕ is the phase angle. The shape of the object in the simulated object was obtained by specifying the range for row and column values in the computer code.

The real objects used were a 3-pin plug and a computer mouse. Figures 7(*a*) and 7(*b*) respectively show the image of the 3-pin plug covered with fringes and the result
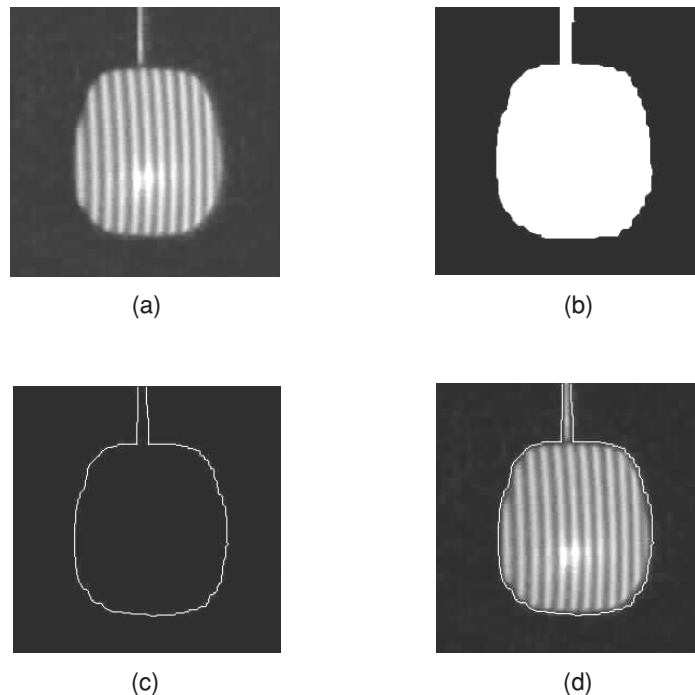

Figure 7   Results of automatic edge detection of fringe patterns for 3-pin plug: (a) Original fringe pattern, (b) results after stage (vii) of processing, (c) detected edge, (d) edge superimposed on original fringe pattern
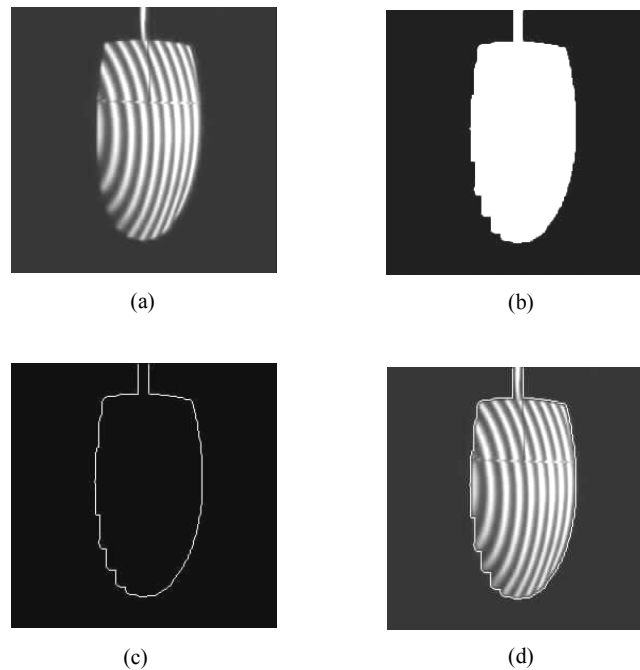
(a)

(b)

(c)

(d)

Figure 8 Results of automatic edge detection of fringe patterns for mouse: (a) Original fringe pattern, (b) results after stage (vii) of processing, (c) detected edge, (d) edge superimposed on original fringe pattern

after stage (vii) of the processing. Figure 7(c) shows the result of edge detection and Figure 7(d) shows the original fringe pattern superimposed with the detected edge. The standard deviation of noise σ in the image shown in Figure 7(a) is 7.4. The corresponding results obtained for the fringe patterns on a mouse having $\sigma = 14.0$ are shown in Figures 8(a)–(d). In both cases, σ was determined automatically from the four sides of an imaginary square located 10 pixels from the border of the image. Figures 7(d) and 8(d) show that the edge detection has been carried out successfully although the standard deviation of noise in both fringe patterns are different. The success of the technique also indicates that the assumption that the noise is of Gaussian type is acceptable.

5.0 LIMITATIONS OF THE TECHNIQUE

The proposed edge detection method can be shown to result in erroneous results if the object covered with fringe pattern is too close to the border of the image. This is because, during the binary dilation operation (stage (vi)) the dilated image enlarges beyond the border. Shape information is therefore permanently lost during the subsequent erosion operation. This is illustrated by the application of the technique to the fringe pattern on a fan blade shown in Figure 9(a)–(d). Figure 9(b) was obtained after the second erosion. The result in Figure 9(b) shows error in the top and lower

left of the segmented image. This is due to dilation beyond the border of the image. To avoid this error the edge of the object should be at least 20 pixels away from the border of the image. This condition can be easily met during the capture of the fringe pattern image by zooming out sufficiently so that the object is located centrally with sufficient space all around.

The second limitation may be imposed by the assumption that the noise is of Gaussian type. This assumption was used in establishing equation (6). Although other types of noise may exist, image acquisition hardware introduces predominantly Gaussian noise in the image [12]. This assumption produced acceptable results when the detection was carried out on real fringe patterns as shown by the results in Figures 7 and 8, suggesting that the smoothing filter implemented is effective enough in removing the noise. In cases when other types of noise are present, such as impulse noise, the addition of a median filter may effectively remove both Gaussian and impulse noise and produce satisfactory results.

Another limitation of the proposed technique is due to fringe spacing. From analysis carried out using simulated fringe patterns it was found that the detection error increases rapidly when the fringe spacing is increased to beyond about 35 pixels as
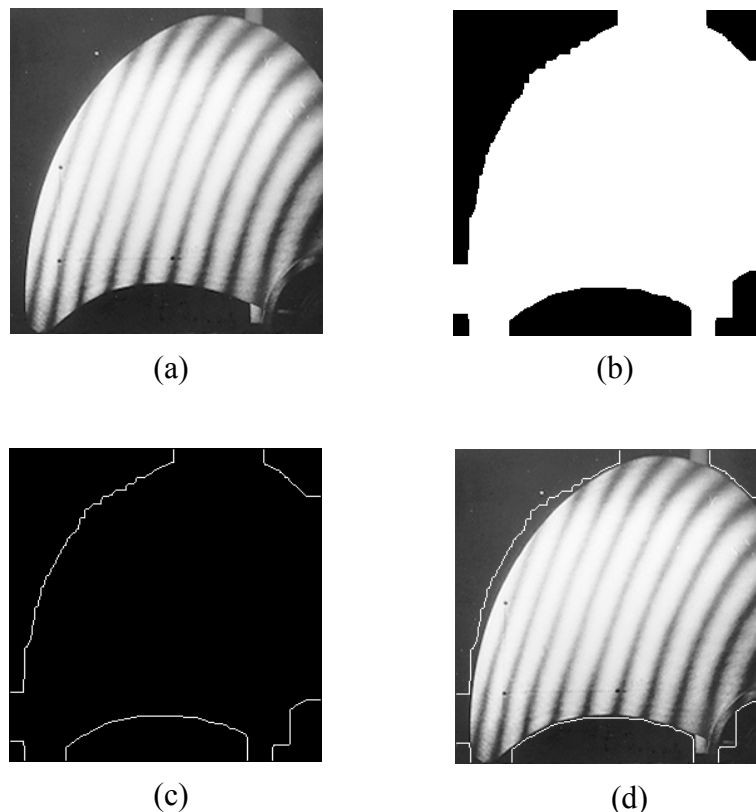

(a)   (b)

(c)   (d)

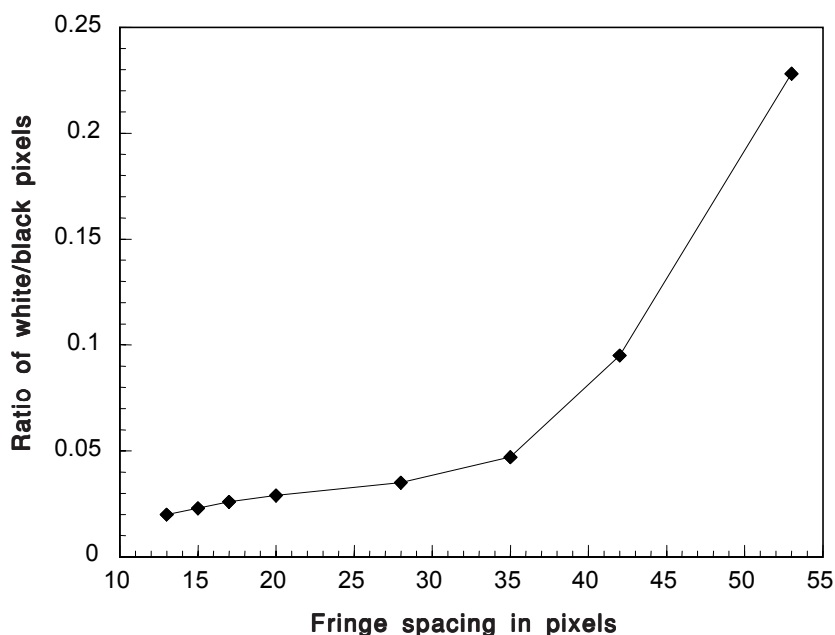**Figure 9**   (a)-(d) Edge detection on fan blade fringe pattern

Figure 10   Effect of fringe spacing on detection error

shown in Figure 10. This is because, when the fringe spacing is too large the binary dilation operation in stage (vi) of the analysis is not sufficient to eliminate all the black pixels in the image produced after the first binary erosion. Thus, subsequent erosion in stage (vii) increases the number the black pixels within the object surface, resulting in an increase in the white/black pixel ratio in the subtracted image. This error can be eliminated by adjusting the number of binary dilations n. This, however, may require some user input, therefore rendering the technique semi-automatic.

6.0   CONCLUSION

An automatic technique for finding the edges of noisy fringe patterns is proposed. The technique involves several stages of image processing including a binarization process with a threshold value that depends on the noise level. The relationship between the threshold value and standard deviation of noise was established from a simulation study. This relationship was used to automatically process the fringe patterns on real objects and locate their edges without user intervention. The main advantage of the proposed technique is the possibility of segmenting the object covered with fringe patterns from the background and performing other operations, such as fringe tracking, onto the entire surface of the object and not just within a predefined window of fixed geometry. The main limitation of the proposed technique is that the detection accuracy is affected by the fringe spacing and further

study is required to enable the technique to operate successfully irrespective of the fringe spacing.

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