Camera focusing based on fringe pattern matching

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A method of camera focusing based on fringe pattern matching is presented. In the method, the variance of the mismatch function is used as a focus measure. The focus measure was examined in a fringe analysis system, and the results from the three well-known focus measures—gray-level variance, image gradient, and Laplacian—were also obtained in the experiment as a comparison. The experimental results show that the focus measure based on fringe pattern matching performs well in peak sharpness, monotonicity, and noise sensitivity and that it has a better performance in noise sensitivity owing to its advantage of averaging noise. © 1997 Optical Society of America

Key words: Focusing technique, focus measure, fringe pattern matching, fringe analysis, optical interferometry.

1. Introduction

Camera focusing is an important technique in machine vision and imaging. This technique is directly related to the accuracy of information in the image acquired from the real world. Many focus measures such as gray-level variance,[1–4] image gradient,[1–3] Laplacian,[1–4] and fringe contrast[5] have been proposed for camera focusing. The focus measures, in practice, are different in their performances mainly in the sharpness of the peak, monotonicity, noise sensitivity, and processing time. It has been found that the gray-level variance is not good in sharpness and that the image gradient, Laplacian, and fringe contrast are sensitive to noise. A better performance in noise sensitivity may be obtained with low-pass filters in practical use.[1]

In this paper a method of camera focusing that is based on fringe pattern matching[6–9] is presented. In the method, the variance of the mismatch function is used as a focus measure for camera focusing. A reference image patch in one fringe pattern and an identical but shifted image patch with the same size as the reference image patch are selected for computing the focus measure. We produce the phase curve of the mismatch function by shifting the image patches with respect to each other, pixel by pixel, and, at the same time, by calculating the mean-square-difference values for each shift. The signal-to-noise ratio of the fringes is significantly improved because each value of the mismatch function is obtained from averaging $M \times N$ pixels if the image patches with the size of $M \times N$ pixels are used in the calculations. Therefore the phase curve obtained from fringe pattern matching, compared with the original fringes, has a better signal-to-noise ratio from the statistical point of view, and it also contains the focusing information of the imaging system because the mismatch function is directly proportional to the square of the modulation of the fringes.

The method of camera focusing based on fringe pattern matching presented in this paper was examined in a fringe analysis system, and it was also compared with the three well-known focus measures—gray-level variance, image gradient, and Laplacian—with the same set of captured fringe patterns. The normalized focus measures and their standard deviations were achieved from 250 captured fringe patterns in the experiment.

2. Principle

The principle of image formation in a camera,[1,2] which is described by a thin-lens model, is shown in Fig. 1. In the figure, P is a point in the object plane and Q is its focused image. The assumed best-focused position is not in the image plane; therefore a blurred or defocused image of P is formed. If the aperture is circular, the blurred image is a circle and it is called a blur circle.[1,2] In this case, a captured

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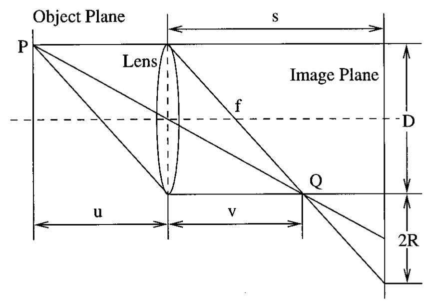

Fig. 1. Image formation in a camera.

image is, in effect, the superposition of the light intensity distributions of many blur circles. Therefore the captured image is degraded in sharpness or contrast.

According to geometrical optics and similar triangles, the radius of the blur circle R can be calculated by[1]

$$R = s\,\frac{D}{2}\left(\frac{1}{v} - \frac{1}{s}\right), \tag{1}$$

or

$$R = s\,\frac{D}{2}\left(\frac{1}{f} - \frac{1}{u} - \frac{1}{s}\right), \tag{2}$$

where s is the distance between the image plane and the lens, D is the aperture diameter, f is the focal length, v is the distance from the focused image to the lens, and u is the distance between the object plane and the lens.

It can be seen from Eqs. (1) and (2) that the size of R is equal to zero when s equals v. This is the case that the best-focused or sharpest image is theoretically achieved. In practice, however, it is difficult or impossible to measure the size of R in many applications. Therefore the focus measure that describes the sharpness of the image is often used for determining whether the image is in focus. In this research, the interference fringe pattern is used as a test object and the presented focus measure is based on fringe pattern matching.

In the case of two-beam interference, the light intensity distribution of the kth captured fringe pattern $I_k(m, n)$ can be written as

$$I_k(m, n) = a_k(m, n) + b_k(m, n)\cos\phi_k(m, n), \quad k = 0, 1, 2, \ldots, \tag{3}$$

where m is the row number and n is the column number of the sampled fringe pattern; $a(m, n)$ and $b(m, n)$ are the background illumination and the modulation of the fringes, respectively; and $\phi_k(m, n)$ is the phase that is normally related to the physical quantity to be measured in optical interferometry; $m = 1, 2, 3, \ldots, M_0$ and $n = 1, 2, 3, \ldots, N_0$ for the image size of $M_0 \times N_0$ pixels.

In fringe pattern matching, the mismatch function for the fringe patterns with vertical fringes can be calculated by[8,9]

$$f_k(t) = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}[I_k(m, n) - I_k(m, n + t)]^2, \quad k = 0, 1, 2, \ldots, \tag{4}$$

where $f_k(t)$ is the mismatch function, $M \times N$ is the image patch size used in the calculation, and t is the phase shift number in the matching process.

Consider a measured value of the mismatch function f_q at any point of the phase curve in a set of samples, which is formed by the addition of noise n_q to the sample mean value $\bar{f}_q$. The measured value f_q is

$$f_q = \bar{f}_q + n_q, \quad q = 1, 2, 3, \ldots, \tag{5}$$

where n_q denotes a zero mean noise process,[10,11] i.e., the expectation that En_q equals 0.

In a measurement of K samples, the standard deviation σ can be calculated by[12,13]

$$\sigma = \left[\frac{\sum_{q=1}^{K}(f_q - \bar{f}_q)^2}{K - 1}\right]^{1/2}, \tag{6}$$

where

$$\bar{f}_q = \frac{1}{K}\sum_{q=1}^{K} f_q. \tag{7}$$

For discussion of the relationship between the standard deviation achieved from 1×1 pixel image patches or one pixel and the standard deviation achieved from $M \times N$ pixel image patches in the measurement, the mismatch function can be rewritten as

$$f_k(t) = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} g_k(t, m, n), \quad k = 0, 1, 2, \ldots, \tag{8}$$

where

$$g_k(t, m, n) = [I_k(m, n) - I_k(m, n + t)]^2, \quad k = 0, 1, 2, \ldots. \tag{9}$$

It can be seen that $g_k(t, m, n)$ is the mismatch function acquired from one pixel or from an image patch of 1×1 pixel. This means that the phase curve obtained from the image patches of $M \times N$ pixels can be expressed as the superposition of $M \times N$ phase curves from one pixel. Therefore each value of the mismatch function achieved from $M \times N$ pixel image patches can be considered as the mean of those from 1×1 pixel image patches.

Assuming that the measurements of mismatch function values based on 1×1 pixel image patches are uncorrelated, one can calculate the standard deviation σ_{MN} for the image patches with $M \times N$ pixels used in the matching process by[11,13,14]

$$\sigma_{MN} = \frac{\sigma_1}{(M \times N)^{1/2}}, \tag{10}$$

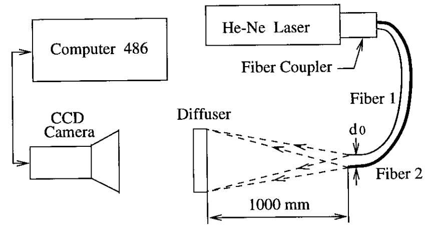

Fig. 2. Schematic diagram of the fringe analysis system.

where $M \times N$ is the number of pixels in the image patches used for the matching process, and σ_1 is the standard deviation acquired from the measurement based on one pixel. It is now clear that the direct determination of fringe contrast from the original fringe pattern is based on the data from one pixel, but the determination made by fringe pattern matching is based on the data from $M \times N$ pixels. Therefore fringe pattern matching has the advantage of averaging noise.

Because the mismatch function in theory is directly proportional to the square of the modulation of the fringes, its variance is in accordance with the sharpness of the fringe pattern. As such the variance of the mismatch function can be used as a focus measure; and the focus measure, like many other focus measures, is a maximum for the best-focused fringe pattern. The focus measure based on fringe pattern matching, M_F, therefore can be expressed as

$$M_F(k) = \frac{1}{T}\sum_{t=1}^{T}[f_k(t) - \bar{f}_k]^2, \quad k = 0, 1, 2, \ldots, \tag{11}$$

where T is the phase shift number in the matching process, and $\bar{f}_k$ is the mean value of the mismatch function, i.e.,

$$\bar{f}_k = \frac{1}{T}\sum_{t=1}^{T} f_k(t), \quad k = 0, 1, 2, \ldots. \tag{12}$$

Above, it is assumed that the fringes are vertical in the fringe patterns. The method is, in effect, also valid for the fringe patterns in which the fringes are horizontal, oblique, or curved. For the fringe patterns with horizontal fringes, $I_k(m, n + t)$ must be changed for $I_k(m + t, n)$ in Eqs. (4) and (9).

3. Experimental Result

The method of camera focusing based on fringe pattern matching was examined with the fringe analysis system as shown in Fig. 2. In the experiment we used a Cohu 4712 CCD camera and a Sigma Macro lens with $f = 50$ mm. The camera settings were Gamma, 1.0; AGC, off; and f-number, 2.8. The interference fringe pattern produced by the two laser beams from the fibers was projected on the diffuser and it was captured for different positions of the focusing lens. The displacement of the focusing lens was approximately 0.1 mm for each step in the experiment.

Figure 3 shows a best-focused fringe pattern, and the intensity in row 255 of the best-focused fringe pattern is shown in Fig. 4. Figure 5 shows the phase curve obtained from the best-focused fringe pattern. A blurred fringe pattern, as a comparison, is given in Fig. 6. Figure 7 shows the intensity in row 255 of the blurred fringe pattern, and the phase curve is

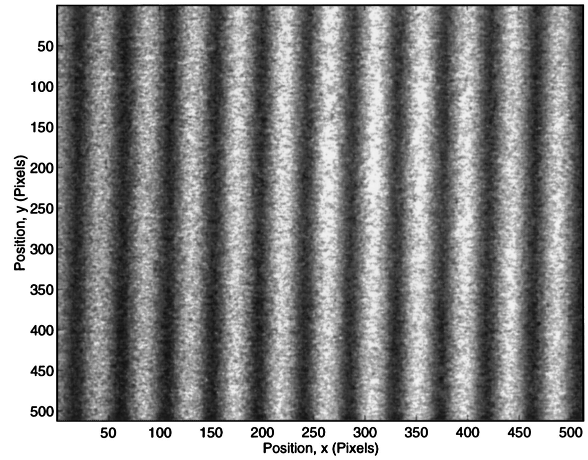

Fig. 3. Best-focused fringe pattern.

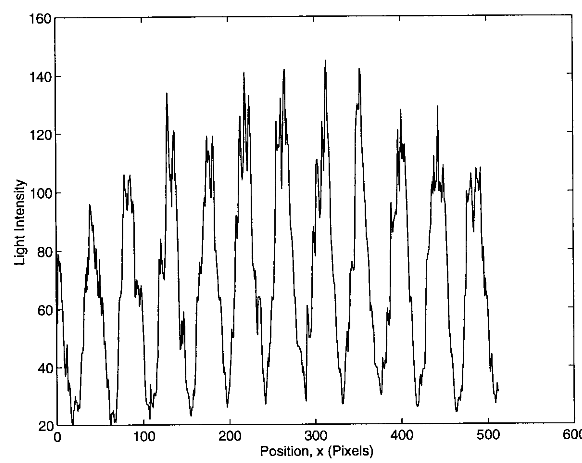

Fig. 4. Intensity in row 255 of the best-focused fringe pattern.

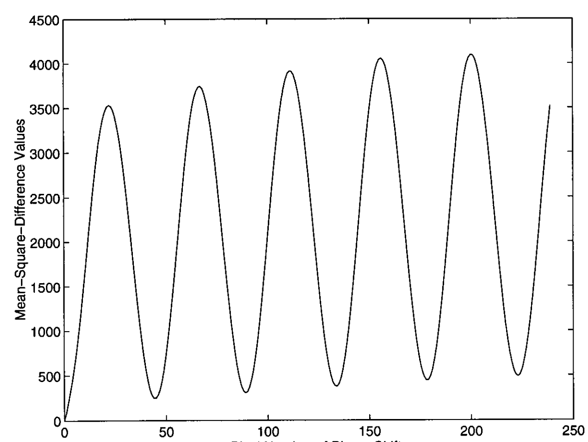

Fig. 5. Phase curve from the best-focused fringe pattern.

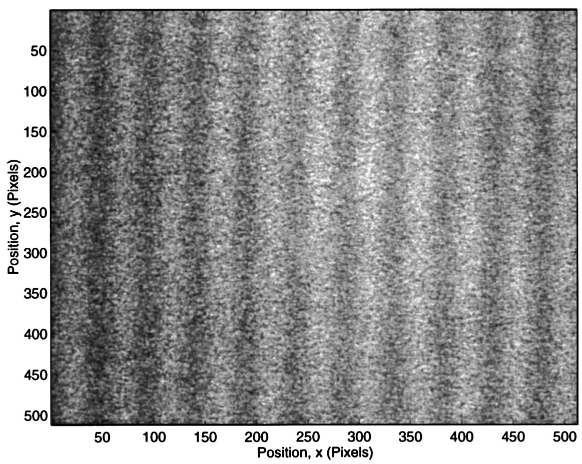

Fig. 6. Blurred fringe pattern.

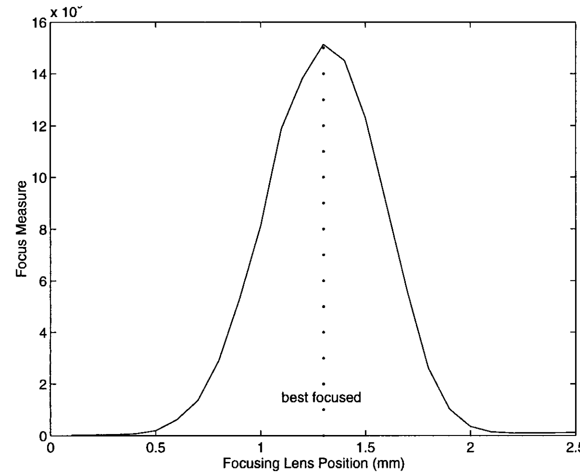

Fig. 9. Focus measure versus focusing lens displacement.

shown in Fig. 8. The focus measure versus the focusing lens displacement is plotted in Fig. 9, and the standard deviation of the focus measure versus the focusing lens displacement is given in Fig. 10. The image patch size of 100 × 512 pixels was used for calculating the focus measure in the experiment. The standard deviation of the focus measure achieved from 250 captured fringe patterns was better than 0.22% of the maximum value of the focus measure.

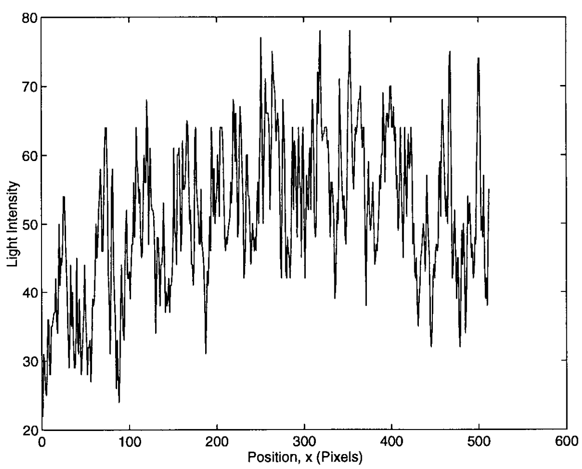

Fig. 7. Intensity in row 255 of the blurred fringe pattern.

4. Discussion

For the discussion of the performance of the focus measure based on fringe pattern matching, the three well-known focus measures[1]—gray-level variance M_1, image gradient M_2, and Laplacian M_3—as a comparison were also computed with the captured fringe patterns for the calculation of M_F in the experiment. The focus measures were normalized to have the same peak values; we accomplished this by dividing their values by their maximums, as shown in Fig. 11. The standard deviations plotted in Fig. 12 were acquired from the normalized focus measures. The mean value of the standard deviation for the focus measure M_F was 0.0005, that for M_1 was 0.0006, that for M_2 was 0.0013, and that for M_3 was 0.0026.

It can be seen clearly from Figs. 11 and 12 that the focus measure based on fringe pattern matching has a sound performance in sharpness of the peak, mono-

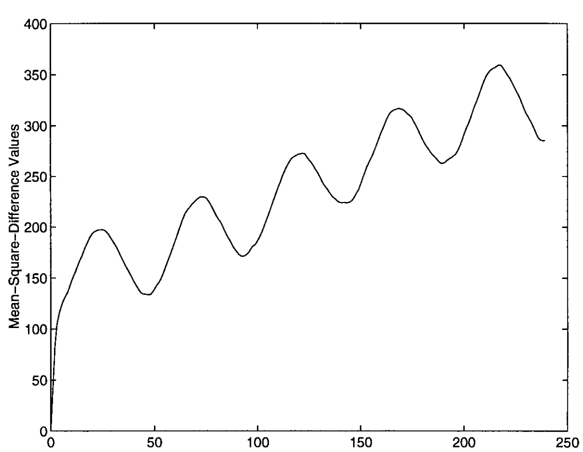

Fig. 8. Phase curve from the blurred fringe pattern.

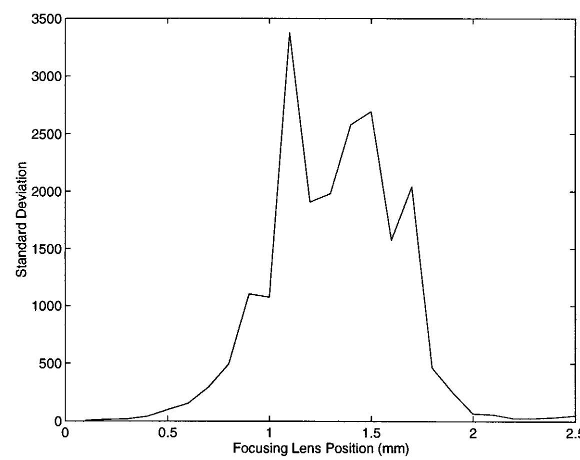

Fig. 10. Standard deviation of the focus measure versus the focusing lens displacement.

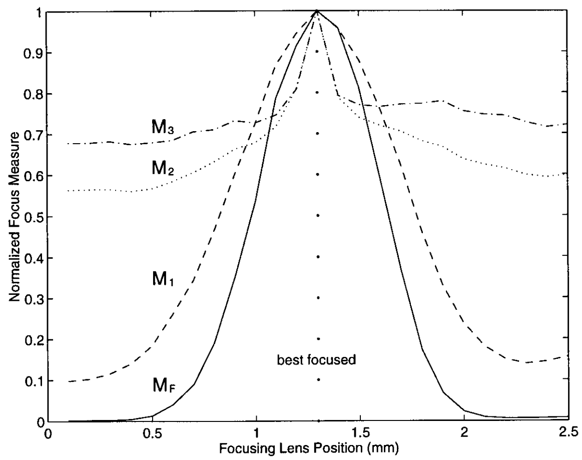

Fig. 11. Normalized focus measures versus focusing lens displacement.

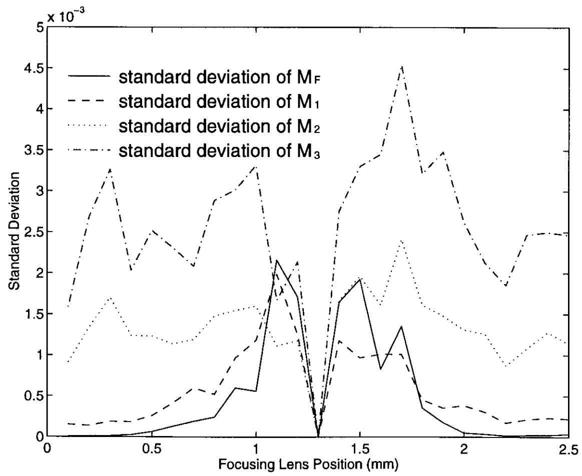

Fig. 12. Standard deviations of the focus measures versus the focusing lens displacement.

tonicity, and noise sensitivity. The disadvantage of the focus measure is that its calculation is complicated and needs more processing time. The focus measure M_1 also has a sound performance in noise sensitivity, but it is not good in sharpness. The focus measures M_2 and M_3 have a better sharpness around the best-focused position, but they are sensitive to noise and their monotonicity is apparently affected by noise.

5. Conclusion

The experimental results have shown that the focus measure based on fringe pattern matching performs well in peak sharpness, monotonicity, and noise sensitivity. The signal-to-noise ratio of the fringes is improved significantly because each value of the mismatch function is obtained from averaging $M \times N$ pixels if the image patches with the size of $M \times N$ pixels are used in the matching process. In practice this method is also useful for fringe-quality analysis. The disadvantage of the focus measure presented in this research is that its calculation is complicated and needs more time in the focusing process.

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